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The research of fourteen countries is represented in this compilation of current and planned research outside the U.S. in tire noise research and tire noise control technology including both passenger car tires and truck tires. Topics covered include mechanisms of tire noise generation, on-the-road and laboratory measurement methods, influence of tire variables (tread type, aspect ratio, material, bias vs. radial, tread wear, sidewall stiffness), operating variables (pressure, temperature, speed, load) road surface variables (texture depth, surface material, wet vs. dry, grooving), tire screens, studded tires, tradeoffs with other design variables such as safety (traction, skid resistance), and recommendations for further research. Included are 104 references.

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U. S. Environmental Protection Agency

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By

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PREFACE

Purpose of Report

The U.S. Environmental Protection Agency is promoting research that will help to develop quieter tires. In order to do this, the U.S. EPA needs to be cognizant of the current state of the art and planned future activity in tire noise research and tire technology, both inside and outside of the United States. The U.S. EPA therefore requested Informatics Inc to compile and update the available information on foreign tire noise research and tire technology.

Method of Data Collection

The information contained in this report was collected by means of inquiries to foreign tire noise contacts, both individuals and organizations. The contacts were queried about their research activities and the names of other individuals or organizations that they were aware of who might be involved in pertinent tire noise research. These referrals were then contacted to ascertain their research efforts. In total, more than 275 contacts were made in 22 countries. The foreign researchers were asked to respond with information about their research on advanced tire developments and tire noise propagation and abatement.

Handling of Data

The information was received in several forms: copies of reports, excerpts from reports or research summaries, and personal communications. Much of the information was received in the original language, so translation into English was required. Translated documents are noted in the reference list by an "A: after the reference number. The collected information was then compiled and analyzed in order to product this report. If more complete information is required by the reader, we urge you to refer back to the individual citations provided herein.

Completeness of Information

The countries contacted and number of references obtained from each are shown in the tabulation below. Materials were received from 64% of the countries contacted (14 out of 22). Five countries--Canada, Japan, Sweden, the United Kingdom, West Germany--provided 73% of all references. It is very likely that their very high show of material in this compilation accurately reflects their position as the leading non-U.S. countries involved in tire noise research. This impression is supported not only by the high frequency of citations from these countries in the tire noise literature, but also from the heavy involvement of investigations from these countries in noise control research in general.

Country	No. of References Obtained	Country	No. of References Obtained
Australia	2	Japan	19
Austria	1	Luxembourg	0
Belgium	0	Netherlands	0
Canada	10	Norway	4
Czechoslovakia	0	Poland	0
Denmark	4	South Africa	1
Finalnd	4	Soviet Union	0
France	3	Sweden	19
Hungary	0	Switzerland	5
Israel	0	United Kingdom	11
Italy	1	West Germany	18

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1. INTRODUCTION

The U.S. Environmental Protection Agency (U.S. EPA) has identified noise from surface vehicles as a significant noise problem in the United States and noise from tires as a principal contributor to this problem. Moreover, as noise from the other parts of the vehicle is gradually reduced through the application of better technology, noise from tires will become a more significant contributor, when the vehicle is operated at high speeds. This report provides an overview of recently completed, current, or planned foreign tire noise research, development, and demonstration projects, and identifies tire industry developments and developing changes in tire technology which may have a bearing or noise.

All data on noise levels are reported in A-weighted decibels, unless otherwise noted.

In organizing this report, the data indicated enough difference between the noise characteristics of truck tires and passenger car tires to warrant treating them separately whenever possible.

2. MECHANISMS OF TIRE NOISE GENERATION

Researchers have postulated five possible mechanisms for the generation of tire noise:

- Inflow and outflow of air from cavities in the tire and road as the tire moves across the road surface ("air pumping")
- Vibration of the body of the tire
- Low frequency airborne sound radiating from the car body due to transmitted vibrations from the tire
- Disturbance of the air as the tire passes through it
- Alternating sticking to the road surface and letting go as the tread rubber deforms ("slip-stick").

2.A Air Pumping

The theory of air pumping as proposed by Hayden (Proceedings of the Acoustical Society of America, 1971) states that as a tire tread contacts the road surface some of the air between the cavities in the tread and the cavities in the road is expelled to the atmosphere. As the tire rolls on, the volume of air remaining in the cavities is in a state of partial vacuum. As the tire continues to roll the tread and road cavities reopen to the atmosphere and air rushes in. This outflow and inflow of air is thought to be a source of noise from tires. A study(96)* by the Australian Road Research Board cites Hayden as stating that air pumping is the most important source of tire noise and that this theory allows modeling of tire noise as noise from a point source. The figure below from a University of Stuttgart study (53) depicts the air pumping generating mechanism.

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* Ref. No. 96.

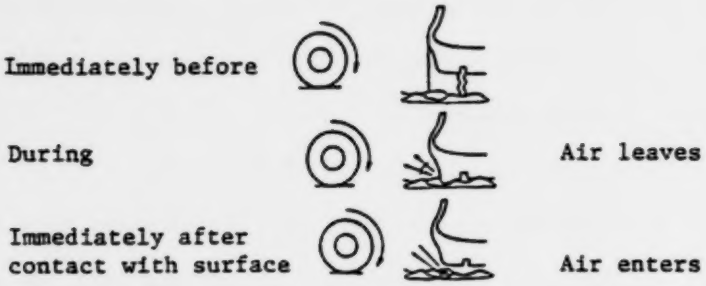


Figure 2-1

The Air Pumping Mechanism (53)

In 1971, the Traffic Environment Research Section of the Public Works Research Institute of the Japanese Ministry of Construction issued a report (42) that states that tread noise is most likely to be generated (and be at higher levels) when the road surface is flat and smooth, because this enhances the ability of the tread pattern to pump air. The peak frequency of tread noise is related to the tread passing rate and can be calculated by the formula, $F_o = v/p$, where:

- F_o = peak frequency (Hz)
- v = peripheral speed of the tire (ft.sec)
- p = pitch of the tread depressions and projections (treads/ft)

A study (38) by the Bundesanstalt fuer strassenwesen (Federal Institute for Street Systems) of West Germany echoes this finding. Their report states that the frequency spectrum of tire noise due to air pumping shifts to higher frequencies as vehicle speed increases.

A study (41) issued in 1974 by the Center for the Evaluation and Research on Noise of the Institute for Transportation Research in France states that the level of noise caused by air pumping depends upon the volume of air expelled and therefore on the size of the cavities in the tire and road. The load on the tire and its internal pressure affect the size of these cavities. The frequency of the sound depends upon the speed of the tire and the spacing of the tread cavities.

2.B Vibration of the Tire

Noise due to vibration of the tire itself is considered to be a significant source of the noise emitted by tires. As stated in a 1976 study (60) by the Ontario Ministry of the Environment, these vibrations of the tire carcass are due to non-uniformities of the tire (mass distribution) and impacts of the tire upon non-uniformities of the road surface (surfact texture). These non-uniformities and impacts set up vibrations in the tire body which are radiated off as as noise.

In a 1978 West German study, it is stated that the surface texture causes two types of vibrations in the tire, radial and tangential. The tangential vibrations will be discussed in a later section. (37) The West German study states that the rougher the street surface the more intense are the resultant radial vibrations and subsequent noise.

In another West German study, it is theorized that the tire which is pre-stressed by its internal pressure acts like a mechanical filter that passes only a certain band width and frequency range from the induced vibrations. This means that the frequency spectrum of vibrational noise does not shift to higher frequencies as vehicle speed increases. The design and material that the tire are constructed of is important in considering vibrational noise because tire resonances depend upon the material of which the tire is made. The West German study also states that a tire without a tread (blank tire) emits higher noise levels due to vibration than does a treaded tire. This is because a blank tire has a greater surface width to contact the road and therefore a greater surface for vibrational stimulation. (38)

2.C Low Frequency Airborne Sound Radiating From the Vehicle Body Due to Transmitted Vibrations From the Tire

A 1974 study (41) issued by the Center for the Evaluation and Research on Noise of the Institute for Transportation Research in France states that in addition to causing noise due to vibration of the tire itself, low frequency radial vibrations in the tire can be transmitted through the vehicle suspension to the vehicle as a whole. Noise is produced when these vibrations correspond to resonant frequencies of the vehicle body parts.

This mechanism can be especially important when interior vehicle noise levels due to tire noise are considered. A research project (59) is underway at the University of Birmingham in Great Britain to look at this aspect of tire noise. They are examining the influence that rolling tire/vehicle interactions have on the vibrational characteristics of the vehicle and the noise generated inside the vehicle structure.

2.D Noise Due to Tangential Vibrations in the Tire

As mentioned previously, contact with the road surface sets up tangential vibrations in the tire. A study (42) by the Traffic Environment Research Section of the Public Works Research Institute of the Japanese Ministry of Construction states that as the rounded tire surface contacts the road surface it is deformed. At high speeds the tread rubber alternatingly sticks to the road surface and lets go due to this deformation. This sets up tangential vibrations in the tire tread and produces high frequency noise. This phenomenon is also called "slip-stick" noise.

A study (10) by Dunlop Ltd. of Great Britain has observed micromovements of the tread of blank tread steel radial tires of up to 2.5 mm as a point on a tread passes through the tire/road contact patch. It has been suggested that this mechanism is the main cause of noise when a smooth tire runs on a smooth surface.

2.E Aerodynamic Noise

A 1974 study (41) by the Center for the Evaluation and Research on Noise of the Institute for Transportation Research in France states that aerodynamic noise from tires is due to variations of acoustical pressure from air turbulence caused by the rotation of the tire. The French study cites Hayden (Proceedings of the Acoustical Society of America, 1971) as stating that the noise produced in this way increases with increasing vehicle speed more than noise from other generating mechanisms, but that it remains negligible in comparison to the noise due to other mechanisms in the speed range currently utilized. It is possible, however, that at higher speeds (greater than 150 km/h) the impact of this mechanism would become more important.

3. MEASUREMENT METHODS

There are essentially five methodologies that can be employed in the measurement of the emission of noise from tires. They are:

- o On the road
  - oo Vehicle pass-by
  - oo Microphone on a moving vehicle
  - oo Microphone on a single wheel trailer
- o In the laboratory
  - oo Laboratory wheel or drum
  - oo Tires on board a vehicle.

Most of the following discussion of these five methodologies come from a 1978 article (37) by Seigfried Ullrich of the West Germany Bundesanstalt fuer Strassenwesen.

3.A On the Road

3.A.1 Vehicle Pass-by

This is the most direct method of measuring the noise emitted from tires. The tires to be tested are mounted on a vehicle and the vehicle is driven over a specific road surface. When the desired speed is reached, the engine is turned off and the vehicle coasts past the microphone position. The maximum noise level is recorded as the "pass-by level." The figure below, from a Finnish study (49) depicts the basic pass-by measurement procedure.

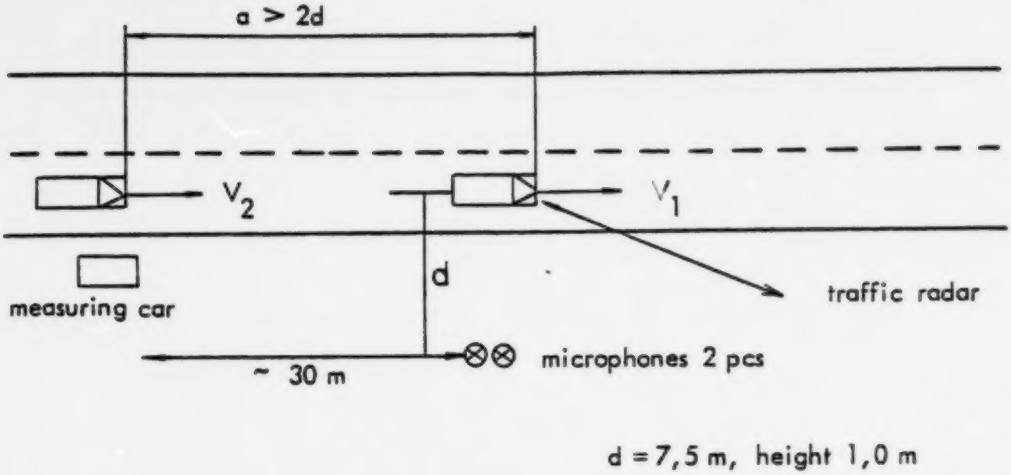

a > 2d
V2
V1
measuring car
d
traffic radar
~ 30 m
microphones 2 pcs
d = 7,5 m, height 1,0 m

Figure 3-1

Pass-by Measurement Procedure (49)
(Diagram shows one side only)

The pass-by measurement method is simple and easy to handle. If measurements are made on both the right and left side of the passing vehicle and the values averaged, the pass-by methodology produces very reproducible results. The averaging of the two measurements compensates for wind, weather, and deviations from the planned microphone distance.

This method allows the influence of the road surface on tire noise to be easily ascertained.

3.A.2 Microphone on a Moving Vehicle

This method involves placing a microphone very near to a single tire on a moving vehicle. The picture below from an Ontario Ministry of Transportation and Communication study (36) illustrates the methodology.

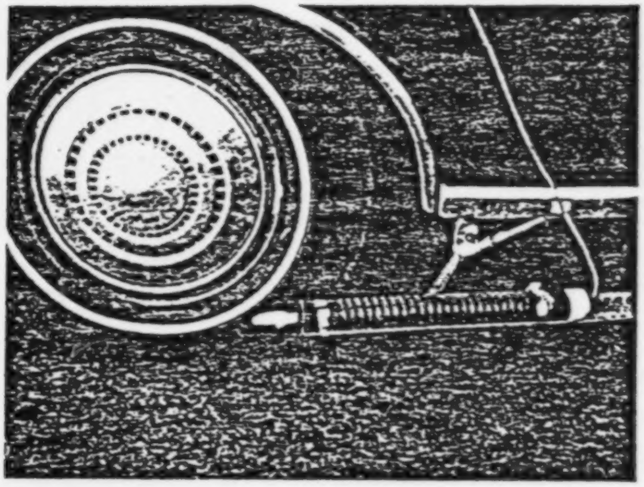


Figure 3-2

Near-Tire Microphone Location (36)

Since the microphone is located outside the vehicle, problems can develop due to air flow noise around the microphone. Preliminary tests in a wind tunnel to measure the intensity of such noises can be made in order to later compensate for them or minimize them by technical measures. Engine noise can also have an interfering effect. Therefore, during measurement runs the engine is normally turned off after the desired speed has been reached.

3.A.3 Microphone on a Single Wheel Trailer

A method very similar to the one described in Section 3.A.2 is to tow a specially constructed trailer behind a moving vehicle. This trailer contains a tire to be tested and a measuring microphone. The picture below from a Swiss Higher Technical College study (4) illustrates the methodology.

Reproduced from best available copy.

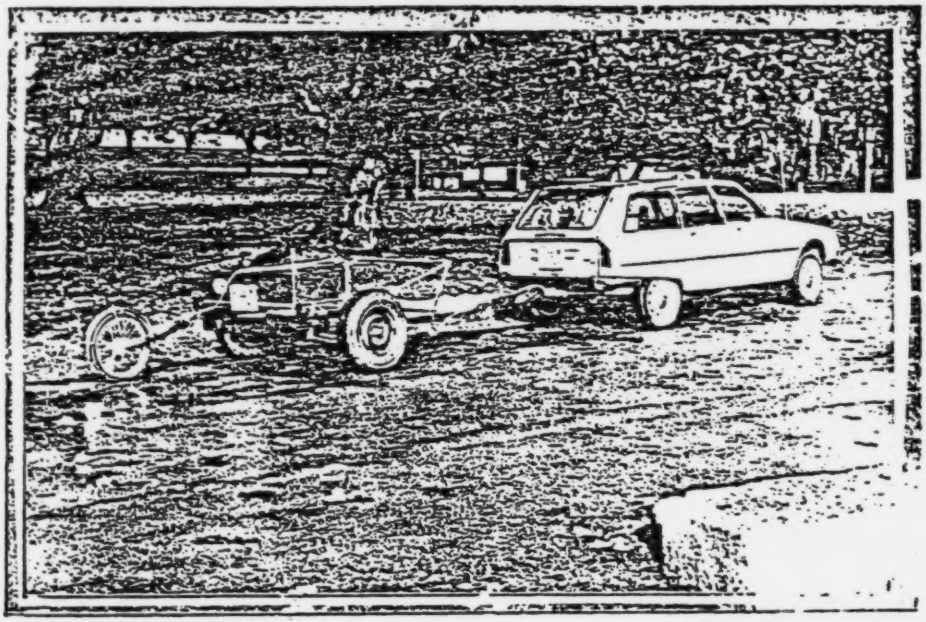


Figure 3-3
Single Wheel Trailer (4)

In order to avoid the effect of engine noises from the towing vehicle and air flow noises around the microphone, the wheel is often covered in a case that includes a sound absorbing lining. The figure on the following page from a University of Stuttgart report (56) illustrates this measurement set-up.

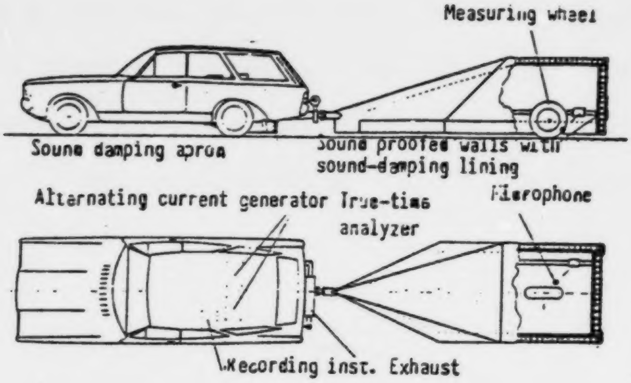

Measuring wheel
Sound damping apron
Sound proofed walls with sound-damping lining
Alternating current generator
True-time analyzer
Microphone
Recording inst.
Exhaust

Figure 3-4
Enclosed Single Wheel Trailer (56)

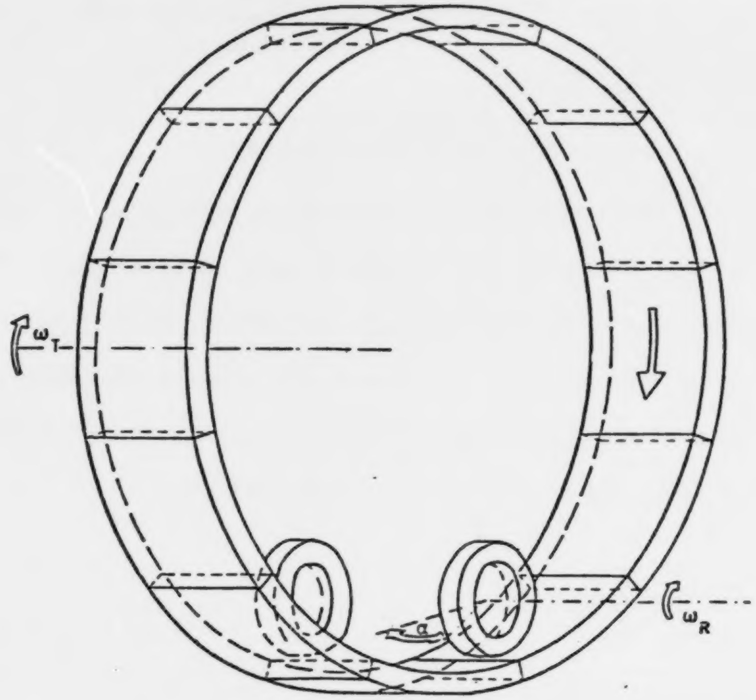
These types of trailered measurement methodologies are suitable for studying the influence of the road surface on tire noise. They have the advantage of allowing measurements in traffic, if the tire is covered in a case. In addition, the tire noise from a particular road surface can be studied over long street sections and a mean value formulated rather than only a single value from a short road section.

3.B In The Laboratory

3.B.1 Laboratory Wheel or Drum

The method of running tires in a laboratory on a wheel or drum is suitable for testing the influence of different tire parameters on tire noise. This type of procedure has the advantage that the measurements can always be carried out under controlled environmental conditions and that only one tire is needed for each variation of a tire parameter.

The tire can be run on either the inside or the outside of the drum or wheel. The figure below from a West German Bundesanstalt fuer Strassenwesen study (38) depicts the internal type.



ω_t= drum drive
ω_r= wheel revolution
α = inclined running angle

Figure 3-5

Internal Laboratory Wheel (38)

The following picture from an Australian Road Research Board report (96) illustrates the methodology where a tire runs on the external surface of the wheel or drum.

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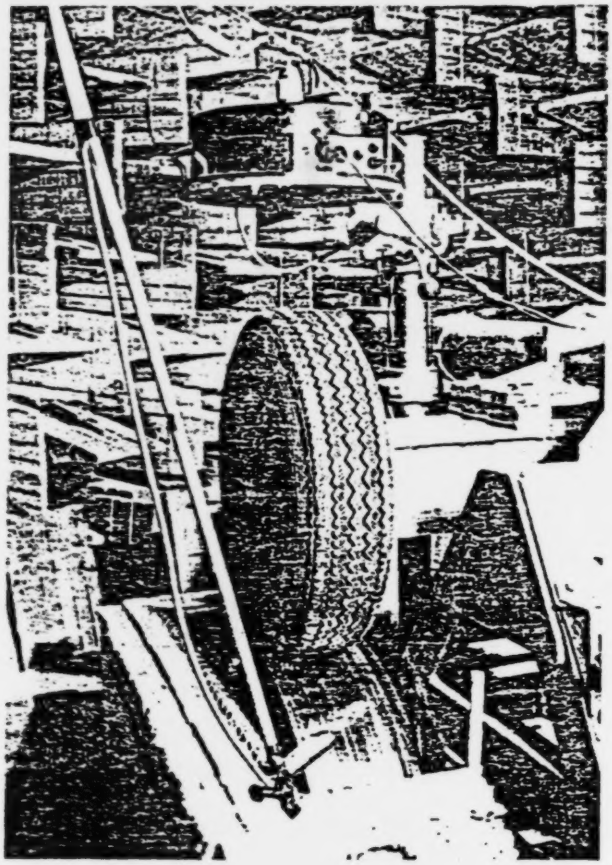

Figure 3-6

External Laboratory Wheel (96)

For the results of wheel or drum laboratory measurements to be comparable with on the road pass-by measurements the following conditions must be met:

- The curvature of the drum or wheel should not be large
- The wheel or drum surface should not be smooth, but covered with a road surface material
- The drum should emit no interfering noise either from its driving mechanism or due to the vibrational excitement of the drum by the rolling tire.

Placing a normal street surface material on the surface of the drum or wheel is easier on the inside of the wheel or drum than on the outside. However, some types of road surface material and textures are difficult or impossible to duplicate on laboratory wheels or drums. This method has, therefore, limitations on the type of road surface/tire interactions that it can measure.

3.B.2 Tires On-Board a Vehicle

This methodology involves running a vehicle on rollers in an anechoic chamber and measuring the resulting noise level. This method has been used in France (at UTAC, south of Paris near Montlhery). (99)

There is a new automotive noise laboratory with a volume sufficient for two of the largest trucks operating on large roll dynamometers.

Plan dimensions of the sound lab are approximately 75 x 75 feet with a ceiling height of at least 25 feet. The interior walls and ceiling are completely covered with rigid (but absorbent) fiberglas protrusions.

Two large roll (at least 48" diameter) chassis dynamometers are mounted in the basement below the chamber with the roll surfaces barely protruding through the floor. A large fully electric motoring/ absorbing unit connects to the roll assemblies through a special flexible sound isolation coupling. Dynamometer capacity is estimated to approach 100,000 pounds gross vehicle weight but tandem axle truck tractors could not be tested unless the rear axle is disconnected.

The entire building sits on an isolation pad and the dynamometer machinery is mounted on a separate large concrete structure isolated from the building. In-cab as well as exterior noise measurements are planned.

4. THE TIRE

4.A Tread Effects

4.A.1 Pitch Variation

In a 1975 Japan Automobile Research Institute, Inc. (JARI) study (44), it was concluded that tire tread noise is due to the arrangement of patterns on the circumferential plane of the tire at an equal pitch or periodicity and that this causes a generation of power at specific frequencies. These frequencies will often be accompanied by secondary and higher harmonics that depend on the type of tire. As an attempt to overcome this problem, pitch variation is now used on all auto tires and some truck and bus tires. This method divides the tread pattern into several segments of differing lengths and arranges them on the tire circumference to disperse the power into many side bands (white noise) rather than specific frequencies. It is difficult to apply pitch variation to lug type tires as this changes their characteristics and reduces their commercial value, according to the study. (44)

In the United Kingdom, Dunlop Ltd. has been active in research into the effects of tread design on tire noise. In a study reported in 1975 (10) the dominant noise frequencies from tread patterns were investigated. According to the report, for the last 35-40 years Dunlop automobile tires have had variable pitch sequences in the tread pattern, which may not alter the overall sound level, but does break up the dominant frequencies. These variable pitch sequences have been developed empirically and have worked well. Now it is possible to use a computer to analyze the harmonics from a tread pattern sequence with a fast Fourier transform. This enables tire designers to optimize the tread pitch sequence. This procedure is regularly used for new snow tires. In addition, variable pitch segments are now being applied to truck tires. The Dunlop Ltd. study cites Richards (May 1974, Journal of Sound and Vibration) as recommending that for block pattern tires, tread grooves be cut diagonally rather than transversely. They should be as circumferential as possible and well staggered from rib to rib. Blocks in shoulder ribs are described as being quieter than blocks in central ribs.

Another Dunlop Ltd. study (5) reported in 1977, states that it is possible to synthesize, analyze, and listen to noise from tread patterns at the design stage by using a digital computer. The first step is to take account of the tread segment pitch lengths and the pitch sequence around the tire. A sawtooth wave is formed as the effect of the tread segments. From this, the program constructs a waveform for the complete periphery of the tire and the waveform is frequency-analyzed. The idea is to include in the program an automatic procedure to search for the best sequence. This is developed by permuting the order of groups of segments. Too many identical length segments adjacent to one another give an undesirable warble in the tire noise. For automobile tires, pitch ratios of up to 2 to 1 can be used. In truck tires, flexibility of the shortest segments can cause non-uniform wear. Therefore, only small ratios can be used.

The study states that if at a certain speed, the dominant frequency due to tread pattern pitch coincides with a tire resonance frequency, the noise level will be increased. By designing the tread pattern to reduce dominant frequencies and to spread the noise into other parts of the frequency spectrum, coincidence with resonance frequencies can be avoided and the noise blends into the background.

The Dunlop Ltd. study cites Mukai (Vol. 28, No. 2, 1974. SAE Journal) as having studied tread pattern noise effects by painting the grooves on a tire tread black and the rest white. The tire was then run on a drum that had paper affixed to its interior surface. A line of photocells was placed across the tread to respond to the black and white pattern. The electrical waveform from the photocells was fed to a loudspeaker to simulate the tread pattern noise for a subjective assessment and was also analyzed for frequency. Present computer noise simulators look at the total groove width along a lateral line across the tread at millimeter intervals. This total groove width variation along the tread segment is fed into a computer along with the segment sequence and lengths. From this the computer produces a simulation of the tire noise. A frequency analysis and subjective assessment are carried out. This allows a differentiation between different tread patterns. This aids in design efforts to angle the grooves and antiphase the patterns on opposite sides of the tread so that there will be less total groove width variation and therefore, quieter tires.

4.A.2 Frequency Spectra

In 1974, the Center for Evaluation and Research on Noise of the Institute for Transportation Research in France issued a report (41) that looked at the effects of tread on passenger car tire noise. The following figure from their report depicts the frequency spectra of three tires: a "conventional radial, a rib tire, and a smooth tire. All had been run on the same asphalt surface under the same conditions.

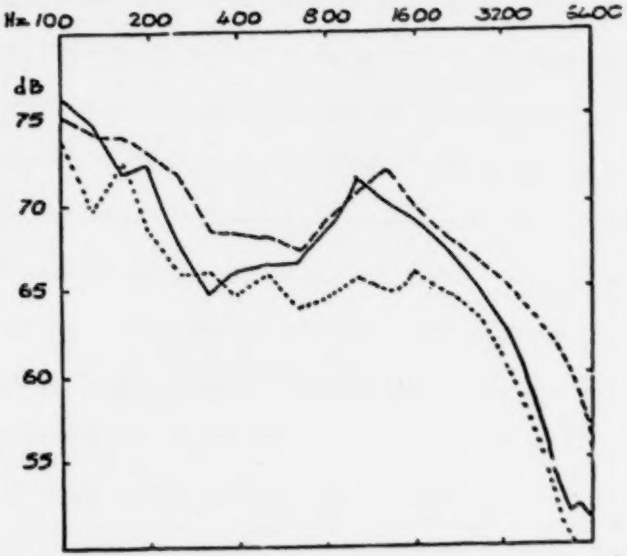

Figure 4-1

Frequency Spectra of Light Vehicle Tires (41)

The chart shows that for nearly all frequencies, the "conventional" radial with complex tread had the highest noise levels and the smooth tire had the lowest. The rib tire had a frequency response similar to the smooth tire except in the range of 650-2500 Hz where it was similar to the "conventional" radial tire.

A 1973 report (43) on truck tires, issued by the Japan Automobile Tire Manufacturers Association, Inc., states that smooth and straight-rib tires do not give sharp frequency peaks due to tread pitch as do EHT (Extra Heavy Tread) lug tires. However, the sound power level for smooth and straight rib tires in the high frequency range over 2 KHz is not significantly different from the sound power level for bias EHT lug tires in the same frequency range. Their study holds that tire noise is considerably affected by primary and secondary spectral consituents and that these are major factors in noise from lug tires.

4.A.3 Groove Volume and Angle

In 1975 the Japan Automobile Research Institute, Inc. (JARI) published a report (44) describing a study that attempted to discover noise reduction measures for truck tires by assessing the noise generated from tires with different numbers and types of grooves. For tires with a single transverse groove in the tread they found that as the width, depth, or length of the groove increased there was an increase in noise level. This was really an increase in the volume of the groove. If the groove volume was held constant while its dimensions changed, there was no change in the noise level. The following drawing from their study depicts the various angles of grooves in a side view of a tire tread pattern. The arrow to the left at the top is the direction of motion. Their research showed that the

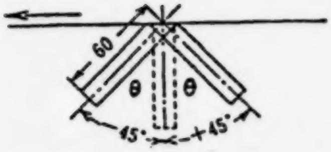

Figure 4-2
Experimental Angles of the Grooves in a Tire Tread (44)

sound pressure level was highest when the angle $\theta = -45^\circ$ and decreased until $\theta = +45^\circ$. This was because $\theta = -45^\circ$ is physically the angle where air pumping is most likely to occur. The amplitude at $\theta = -45^\circ$ is 2.5 times greater than at $\theta = 0^\circ$. At $\theta = -45^\circ$ the sound pressure level is especially high in the high frequency band. The JARI report suggests that changing the angle of the grooves in a tire's tread could be used to reduce its noise without greatly damaging its characteristics. Reduction in noise could also be gained by reducing the volume and shortening the length of the grooves. The change from lug pattern tires to rib-lug tires is an example of this type of noise reduction methodology.

4.A.4 Tread Varieties

At the Federal Institute for Street Systems in Cologne, West Germany, various passenger car tires were tested for noise levels on their rolling test stand. A study (38) reported in April of 1978 looked at tread patterns as one parameter. They examined the noise level from steel belted tires of sizes 185 SR 14 and 155 SR 13 from 19 tire manufacturers. The noise levels covered a range of 5 dB with no tire significantly quieter or louder than the others. The researchers guessed from their results that significantly quieter tire makes exist, but they could not make this a firm conclusion because of the need for more measurements. They intend to continue their research in this area.

In a study (9) reported in 1975 that dealt mainly with the influence of pavement textures on tire noise, the Research and Development Division of the Ontario Ministry of Transportation and Communication addressed briefly the matter of differing noise levels from differing tread patterns. Their report states that tire tread design has a maximum 5-6 dB effect on pass-by noise from cars and a 10-13 dB* effect for trucks.

In 1975 the Japan Automobile Research Institute, Inc. issued a report (44) that looked at four types of tread patterns: lug, rib, rib-lug, and block. They found that lug tires have the largest air pumping effect and the highest noise levels. Their results showed that for rib-lug tires, the noise level depends on the percentages of rib and lug patterns that were in the tire. Block tire tread patterns used on trucks and buses as snow tires had noise levels close to that of lug tires. Radial block tread tires were slightly noisier than bias rib tread tires. They found that bias-structured lug tread tires were the loudest type of tires for trucks and buses.

In France, the Center for Evaluation and Research on Noise of the Institute for Transportation Research has looked at the effects of tread on tire noise. In 1974 they reported a study (41) that included a summary of the results of experiments by others on tire noise. They stated that basically lugs (or crossbars or transverse grooves) in a tire tread permit traction and effective braking. Ribbed tires with longitudinal grooves permit road holding. Recapped tires have different designs and usually fit in between transverse (lug) and longitudinal grooved (rib) tires in characteristics. Tires for heavy vehicles fit fairly easily into these

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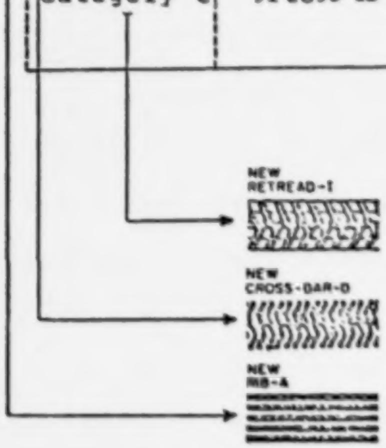
*All measurements are in A-weighted decibels unless otherwise noted.

Truck Tires

Category A	77 to 82 dB
Category B	82 to 90 dB
Category C	91 to 98 dB



Passenger Tires

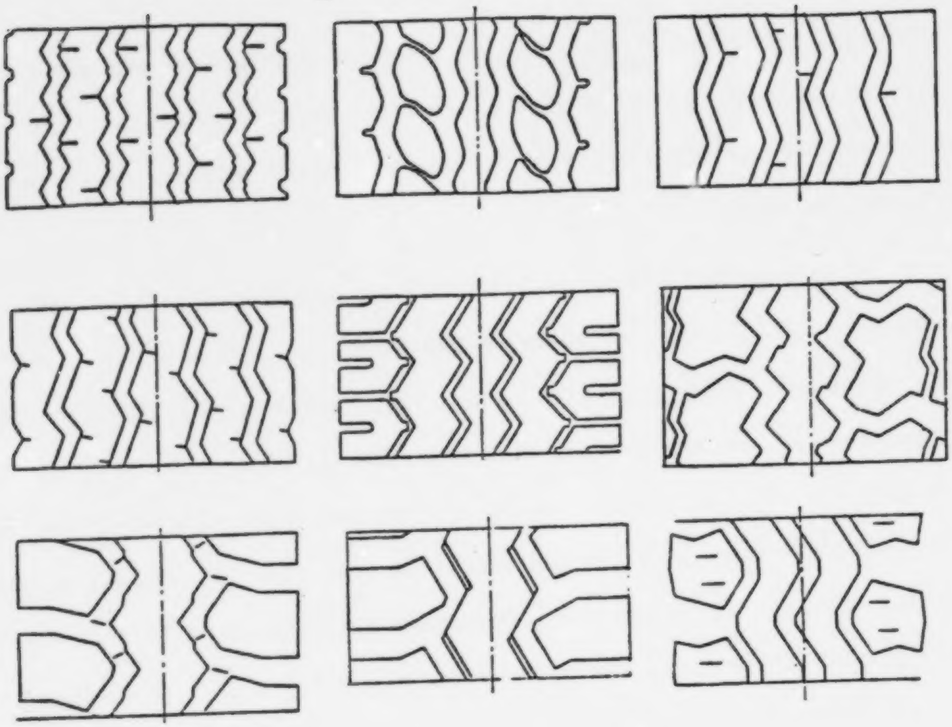
"Smooth" tire*	62 dB
Rib tires	64 dB
Conventional tire	65 to 70 dB
Snow tire	74 dB
Studded tire on the order of	80 dB

Smooth: pneumatic tire with geometric characteristics identical to a new tire, but without tread design.

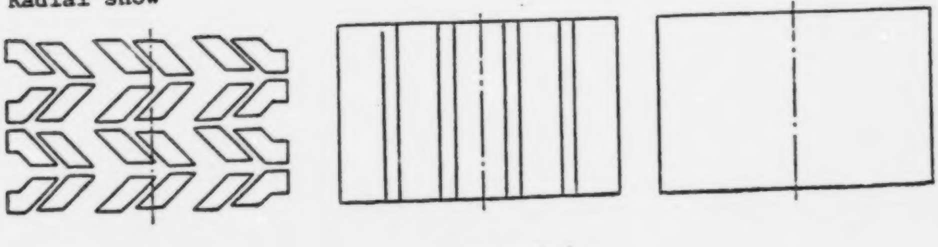
Figure 4-3

Sample Noise Levels From Various Types of Tread Patterns (41) categories. Those for light vehicles are more complex and are not as easily classified. The following chart from their report shows representative noise levels for different types of tread patterns at 80 km/h at 7.5 m distance.

In July and August of 1973, the Japan Automobile Tire Manufacturers Association, Inc. conducted tests on the Japan Automobile Research Institute test course with truck/bus tires (43). They tested many different types of tires: bias EHT and HT lug, bias EHT rib-lug, bias snow, bias HT rib, bias rib semi HW, radial lug, radial rib, radial snow, bias straight-rib, radial straight-rib, bias smooth, radial smooth, bias 30% abraded HT rib, and bias 70% abraded HT rib. The following classification defines their terminology: EHT = Extra Heavy Tread (deep grooves), HT = Heavy Tread (general grooves), HW = Highway (shallow grooves), and Semi HW = tires specially made for high speed driving but within the range of general groove depth. The following two figures from their report show the tread patterns of the tires tested in their research.



Radial-lug type



Radial snow

Radial straight-rib

Radial smooth

Figure 4-4

Pattern Drawings (Radial Structure) (43)

Their test procedure involved measurement of the vehicle noise level during pass-by with the engine idling on an asphalt roadway. They found among the truck/bus tires tested that bias lug EHT and HT tires were the noisiest. Radial rib type tires were the quietest. The following are the noise levels averaged over all speeds (40, 60, 80, 100 km/h) [sic] at 7.5 m and 100% load:

bias lug EHT and HT	85 dB
radial rib	76 dB
bias HT rib	79 dB
bias snow	82 dB

The tire noise spectra of lug pattern tires showed a sharp peak at 250-500 Hz at all speeds. Rib tires did not give a peak. Their research found larger differences between types of tires than between brands within the same type. For example:

- six brands of HT bias rib tires showed 1.4 dB difference
- five brands of semi-HW bias rib tires showed 2.3 dB difference
- three brands of radial lug tires show 0.7 dB difference

The 1973 JATMA study showed that in the speed range of 40-100 km/h, general truck/bus tire noise ranged from 70 to 93 dB at 7.5 m. They were able to place the different types of tires on a continuum based on noise level: smooth $\leq$ straight-rib $<$ rib $<$ snow $<$ lug. Smooth tires were generally 3-4 dB quieter than rib tires.

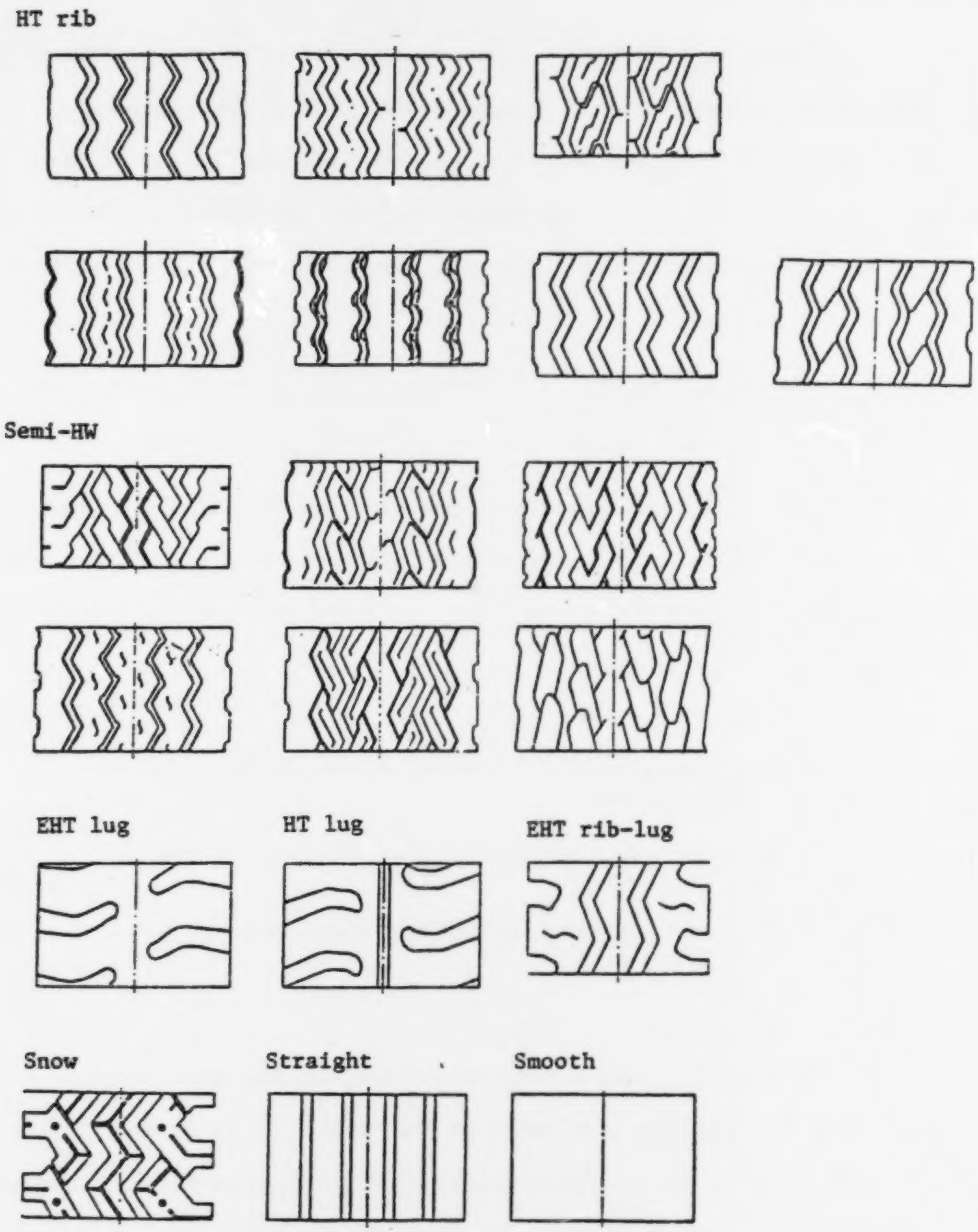

HT rib
Semi-HW
EHT lug
HT lug
EHT rib-lug
Snow
Straight
Smooth

Figure 4-5

Pattern Drawings (Bias Structure) (43)

The basic conclusion of the study was that smooth and straight straight-rib tires produced the lower limit in tire noise but that these tires did not satisfy user requirements for durability, traction, driving safety, and shock absorbability. They therefore called for the utilization of conventional rib pattern tires and for continued research efforts toward reducing tire noise levels as close as possible to the levels of smooth and straight-rib tires without jeopardizing safety considerations.

4.B Physical Attributes of Tires Related to Noise

4.B.1 Aspect Ratio

The aspect ratio of a tire is the sectional height divided by the sectional width. The result is expressed as a percentage. For example, an 85 series tire would have a height that is 85% of its width and a 60 series tire would have a height that is 60% of its width.

A 1975 report (10) by Dunlop Ltd. of the United Kingdom on tire/road noise briefly addressed the difference in noise levels from tires with different aspect ratios. They found that 60 series tires are 0.7 dB noisier than 80 series tires on smooth asphalt and 1.2 dB noisier on motorway concrete. The following figure from the report summarizes their results.

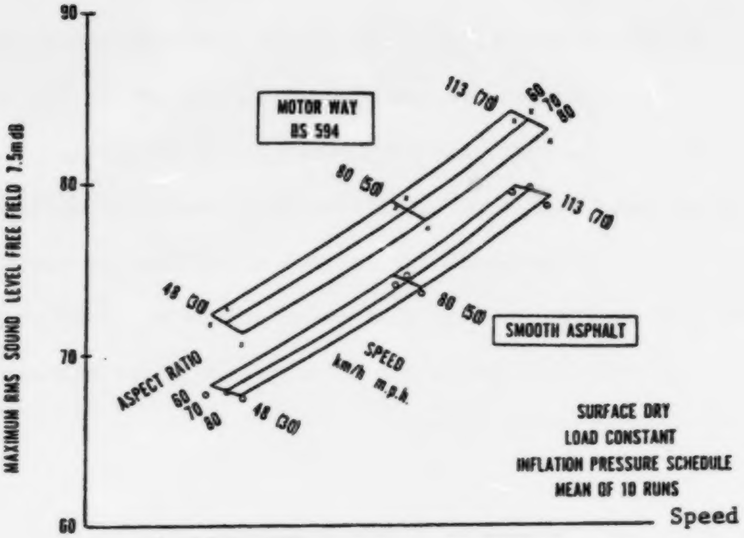


Figure 4-6

Lattice plot effect of aspect ratio, constant sectional width, 185 series 13-in serrated rib tyre (10)

The Dunlop Ltd. report mentions other results by Hillquist and Carpenter that show that 60 series bias belted tires are 2 dB noisier than 78 series tires.

The Federal Institute for Street Systems in West Germany issued a study (38) in 1978 that states that at 100 km/h the noise levels of low aspect ratio automobile tires of 70, 60, and 50 series were up to 1.8 dB greater than those from "normal" aspect ratio tires. The mean difference between the "normal" and "low aspect" tires was 1 dB.

The National Road and Traffic Research Institute of Sweden issued a report (32) in 1976 entitled Tire Dimensions, Properties of Wide and Low Versus Narrow and High Tires. This work grew out of an earlier Swedish research project which indicated that it would be possible to construct tires with lower noise by accepting a radical change in their dimensions. The earlier work concluded that a positive effect on noise was possible if tires were narrower and higher than normal. However, the current trend is to wider and lower tires.

During the last 15 years the aspect ratio of automobile tires has decreased from 95% to 50-80% for "modern" tires. Low aspect ratio tires have gained wider use due to their better handling characteristics and higher speed ratings. The National Road and Traffic Research Institute also suggests that the visual appearance of low aspect ratio tires has been a factor in their increasing popularity.

The figure below from a 1977 Dunlop Ltd report (82) illustrates this trend toward reduced aspect ratio tires. While some production cars now have 50% aspect ratio tires, some racing car tires have been produced with aspect ratios as low as 28%.

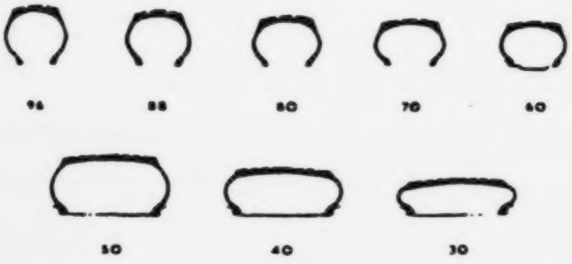
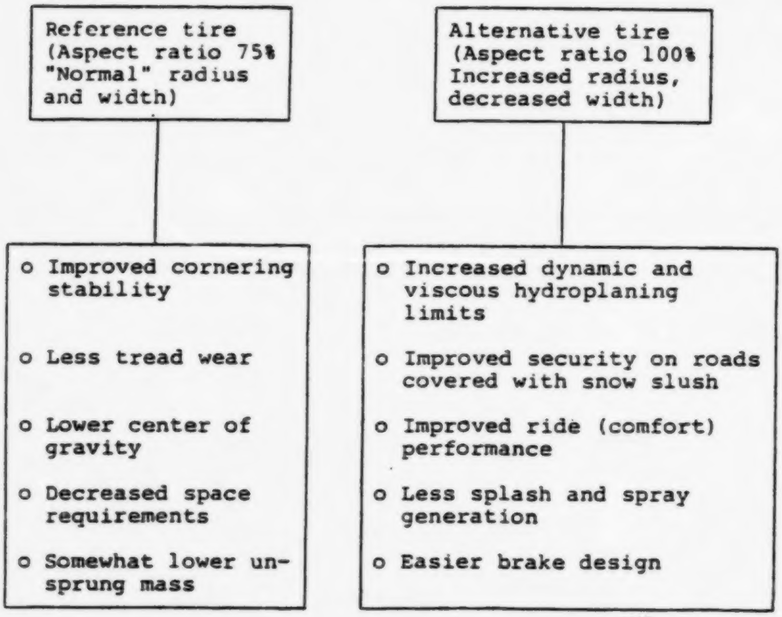


Figure 4-7

The progression towards reduced aspect ratio car tyres (82)

The Swedish research reported in 1976 (32) examined the effects of dimensional changes on important performance characteristics and sought to determine if a quiet tire based on dimensional changes could be a realistic alternative to present noisy tires. The research looked at tires that were 25% narrower and 25% higher than normal, reference tires, but with the same cross-sectional area.

The figure below from their report summarizes their findings as to the positive characteristics of the two types of tires.



Reference tire
(Aspect ratio 75%
"Normal" radius
and width)

o Improved cornering stability

o Less tread wear

o Lower center of gravity

o Decreased space requirements

o Somewhat lower unsprung mass

Alternative tire
(Aspect ratio 100%
Increased radius,
decreased width)

o Increased dynamic and viscous hydroplaning limits

o Improved security on roads covered with snow slush

o Improved ride (comfort) performance

o Less splash and spray generation

o Easier brake design

Figure 4-8

Positive Characteristics of High and Low Aspect Ratio Tires (32)

The conclusion that they reached is that it is not possible to judge which type has the best overall characteristics. Each tire should be appraised according to its expected use. They do say that use of a high ratio tire would be motivated in situations requiring minimum noise generation.

4.B.2 Tire Width and Diameter

In their study reported in 1978 (38) the Federal Institute for Street Systems in West Germany looked at the influence of tire size on noise level. They compared various sized steel belted truck tires with the same tread at 50 and 100 km/h and found that the following relationship describes their results:

$L \sim 30 \log (\text{tire width})$

where L = the noise level in dB

Their study suggests the following relationship to describe noise from passenger car tires of differing sizes:

$L \sim 10 \log (\text{tire width})$

where L = noise level in dB.

In both cases no units were specified for the tire width.

Verband der Automobilindustrie E.V.(VDA) produced a book (54) entitled Urban Traffic and Noise in 1978. In their section on tire/road noise they state that for truck tires, rolling noise decreases sharply as the width of the tires decreases. A halving of the width of the tire decreases rolling noise by 9 dB. In addition, twin tires are 6 dB quieter than one single tire with the same overall width. They recommend investigating the possibility of putting twin tires on all commercial vehicles and buses, including on the steering axles.

A 1975 Dunlop Ltd. report (10) states that with a constant load, 145 section width 13 inch tires are 2.5 dBA quieter than 185 section width 13 inch tires. The figure below from their report summarizes their results.

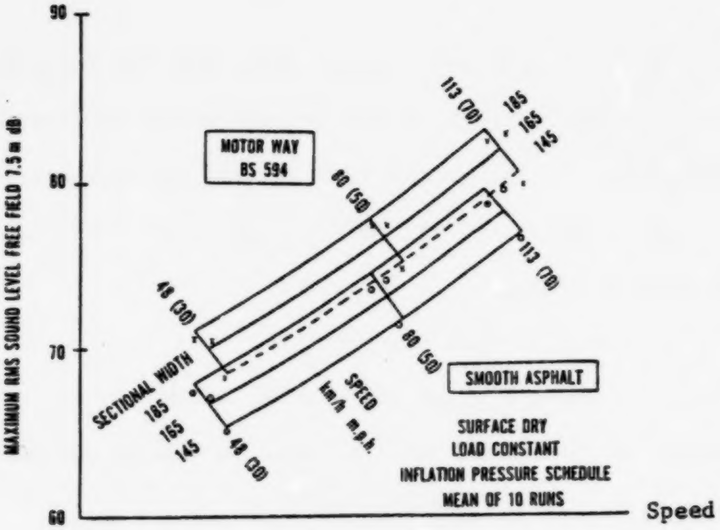


Figure 4-9

Lattice plot effect of sectional width, constant aspect ratio, 80 series 13-in serrated rib tyre (10)

In addition, the Dunlop Ltd. report states that for block pattern tires of the same section width and tread width, 10 inch tires are 1.2 dB noisier than 13 inch tires.

4.B.3 Material

It appears that little effort is being applied to research on the effects of tire compounds on the noise level. Only one study was found that even addressed the area. According to the 1975 study for truck tires, smooth tires of high hysteresis tread rubber are 1 dB noisier in dry situations than natural tread rubber smooth tires and high hysteresis rubber traction tires are 1 dB quieter than natural tread rubber traction tires. In wet conditions both tread patterns with high hysteresis rubber are 1.5 dB noisier. For cars in dry situations on smooth asphalt, high hysteresis serrated rib tires were 0.9 dB quieter. On concrete motorway they were 1.7 dB quieter (10).

French work (19) has shown that over a period of two years the rubber of a tire will harden slightly and the resulting noise level can increase by 1-2 dB.

In a related area, it has been suggested that a light alloy wheel is 1.5 dB quieter than a steel wheel (10).

4.B.4 Sidewall Stiffness

No material was uncovered that discussed the relationship between the stiffness of tire sidewalls and the noise level from those tires.

4.B.5 Bias vs. Radial

Trucks.--According to a 1977 study (82) by Dunlop Ltd., of the United Kingdom, there has been an overall shift to radial tires in Europe. The study reports that the trend in truck tires is toward steel radial tires and that 85-90% of all truck tires and 80% of original equipment truck tires will be tubeless radials by 1980.

In 1973 (43), the Japan Automoblie Tire Manufacturers Association, Inc. found that radial tires of both lug and rib tread patterns are 5 dB quieter than bias tires. Their research showed a difference between motorized pass-by tests and coasting pass-by tests for all speeds of approximately 5 dB for bias tires and 7 dB for radial tires. They therefore concluded that bias heavy tread tires produced 30% of total vehicle noise while radial rib tires produced 20%.

Cars.--The VDA of West Germany reported (54) in 1978 that if a crossply tire with a ribbed tread is compared with a radial tire of the same tread, the latter will show a slightly lower rolling noise level. The Japan Automobile Research Institute, Inc. in a 1975 report (44) states that it is generally known that bias tires exhibit a higher noise level than radial tires. They based this statement on prior work on tire noise conducted in Japan.

Dunlop Ltd. tested bias and radial winter block pattern tires of the same tread depth on a drum. Their report (10) states that the radial tire was 0.7 dB quieter than the cross ply tire. Dunlop speculates that this is due to the fact that for radial ply tires there is less tread shuffle or micromovement on the road.

A study report in 1975 by the Norwegian Road Research Laboratory (35) produced the only results that conflict with the common view that radial tires are quieter than bias tires. On a smooth road, for car tires, they found no difference between the noise from bias and radial ply tires. On rough surfaces, however, radial tires caused an increase in the noise level of 3 dB over that from bias ply tires. It is possible that these results might be questioned due to the limited number of measurements made on only one car and because different tread patterns were used for the different types of tires.

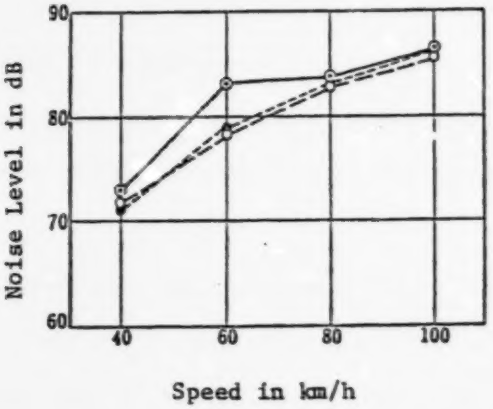
4.B.6 Wear

The VDA of West Germany state in their 1978 book, Urban Traffic and Noise (54) that tread depth is often pointed to as having an effect on tire noise. Their book states that new tires are usually quieter than tires that are half worn. As wear increases further, noise levels decrease once more.

Dunlop Ltd. (10) in a 1975 study states that from the new to half-worn states, noise typically increases 2.5 dB for rib tires and 4.2 dB for cross-bar tires. As the fully worn state is approached, the noise level decreases unless the tread is full of pockets of air that can be trapped at advanced stages of wear. Dunlop reports that irregular wear tends to occur on truck tires, especially during high speed driving in an unloaded state. This type of wear can increase the noise emitted by the tire.

stages of wear. Dunlop reports that irregular wear tends to occur on truck tires, especially during high speed driving in an unloaded state. This type of wear can increase the noise emitted by the tire.

A 1973 study (43) by the Japan Automobile Tire Manufacturer's Association Inc. (JATMA) did not find this same increase in noise level at the partially worn state. According to their results for bias rib truck tires, the noise level tends to decrease as wear continues from a new tire through 70% abraded, although the effect is not large. Their research shows that when a bias rib tire is 70% abraded the noise in the 2-3 KHz frequency region becomes more dominant. The figure below from their report displays the results of their research.



Where ⊙———⊙ = new bias Heavy Tread tire, ○- - - - - -○ = 30% worn, ●- - - - -● = 70% worn, Load = 100%

Figure 4-10
Noise From Truck Tires as a Function of Wear (43)

A 1975 report (9) by the Ontario Ministry of Transportation briefly discusses this topic. The report claims that tire tread wear has a maximum 2 dB effect on the pass-by noise levels of passenger cars and a maximum 5-7 dB effect for trucks, but it is not stated in which direction.

The Japan Automobile Research Institute, Inc. (JARI) reported a study (44) on truck lug tire noise in 1975. Their report states that the center of a tire tread tends to wear out faster and this changes the pressure distribution and dimensions of the contact surface. According to their study, lug tires are very sensitive to wear. Their noise level first increases with wear and later gradually decreases as wear continues. The JARI report states that rib tires are not significantly affected by wear.

In 1974 the Center for the Evaluation and Research on Noise of the Institute of Transportation Research in France issued a study (41) on the theoretical and experimental aspects of tire noise. In reference to the effect of tire wear on noise they state that the variation in sound emission is most often due to the fact that wear is irregular and that the subsequent distribution of stresses on the tire/road contact surface differs. Their report also cites Flanagan's findings (Automotive Engineering, April 1972) that increased tire noise from worn tires is due to the greater area of contact that a worn tire has with the road.

The drawing below from the French study illustrates this loss of curvature and greater contact with the road.

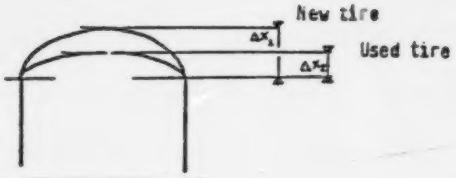


Figure 4-11

Loss of Tire Curvature Due to Wear (41)

At 80 km/h and 7.5 m distance a new tire showed a noise level of 83 dB. When that tire was milled to the curvature of a used tire its noise level was 88 dB. When milled again to a new tire curvature the noise level was 82 dB. A different used tire used as a reference gave a noise level of 90 dB.

4.C Tire Operating Variables Related to Noise

4.C.1 Pressure

One study finds that noise increases with pressure, one that it decreases, and one that there is no significant influence.

A 1978 book Urban Traffic and Noise (54), by Verband Der Automobilindustrie (VDA) of West Germany states that in straight-ahead driving the effect of inflation pressure on noise level is only slight and can be virtually neglected in the case of cars. In 1977 a study (57) issued by the Research Institute for Motor Transport Service and Vehicle

Engines of the University of Stuttgart echoed this finding. The study states that tire pressure in the range that normally occurs in passenger cars has no significant influence on noise emissions.

In 1975 the Japan Automobile Research Institute, Inc. (JARI) issued a study (44) that briefly addresses the subject of the effect of inflation pressure on noise emissions from truck tires. Their research showed that noise from lug type tires was particularly sensitive to changes in the internal pressure of the tire. The figure below from the JARI report illustrates their findings that the noise level decreases as inflation pressure increases, particularly from 2.0 kg/cm^2 to 4.0 kg/cm^2 (1 kg/cm^2 = 14.2 psi).

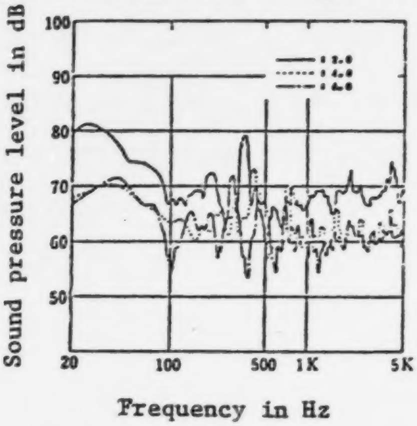


Figure 4-12
Variations in Sound Pressure Level of Standard Single Groove by Internal Pressure, where Load = 1000 kg, speed = 100 km/h, and pressure is in kg/cm^2

The JARI report also states that the primary harmonics of tire noise shift to lower frequencies with an increase in inflation pressure. In addition, they found that the resonant frequency of a tire shifts to higher frequencies with an increase in the inflation pressure.

In 1974 the Center for the Evaluation and Research on Noise of the Institute of Transportation Research in France (CERN) issued a report (41) on the theoretical and experimental aspects of tire noise. The report states that since the range of variation of the inflation pressure of a tire is small, the effect of pressure on sound emission is not very large. The report states that the maximum change measured does not exceed 3 dB, but it is not stated whether standard inflation pressures were used to obtain this result..

The CERN study concludes, however, that the frequency of noise from longitudinally grooved tires is affected by changes in the internal pressure of the tire. Changes in inflation pressure change the contact area between the tire and road surfaces. Decreased pressure increases the area of contact, increases the length of tire grooves on the road, and shifts the noise peak to lower frequencies. Increased pressure has the opposite effect. This relationship is described in the following formula:

$$F = \frac{c}{2 \times l}$$

where F = frequency

c = speed of sound in air

l = length of groove

The following table, from their report, provides examples of the results of this relationship. Their study states that observed frequencies from tests agree with the expected frequencies calculated from the formula.

Tire with longitudinal grooves		length	frequency
Rear tire	Maximum pressure	11-13 cm	1500-1300 Hz
	minimum pressure	13-15 cm	1300-1100 Hz
Front tire	Maximum pressure	15-19 cm	1100-900 Hz
	Minimum pressure	16-22 cm	1100-800 Hz

Table 4-1

Length of Tire Tread Groove and Tire Noise
Frequency Based on Internal Tire Pressure (41)

As part of a study (38) reported in 1978 by the Federal Institute for Street Systems in West Germany, the effect of internal tire pressure on noise emission was investigated. The pressure in their tests was varied in three stages; 1.5, 2, and 2.5 bars.* They found that tire noise increased by 0.4 dB when the pressure was increased from 1.5 to 2 bars and from 2 to 2.5 bars. The study states that the following equation describes the relationship between noise level and tire inflation pressure.

$$L \sim 5.5 \log (\text{inflation pressure})$$

where L = noise level; (no units given).

4.C.2 Temperature

Very little information was uncovered concerning research on the effects of tire temperature on tire noise emissions. This is probably due to the widely held belief that temperature has little if any effect.

A report (41) in 1974 by the Center for Evaluation of Research on Noise of the Institute for Transportation Research in France concludes that temperature is not an essential variable to be considered. The Ontario

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* 1 bar equals approximately 1 atmosphere

Ministry of Transportation and Communication concluded as part of a 1975 study (9) that tire temperature has no effect on the sound level from either passenger car or truck tires. Finally, a report (10) by Dunlop Ltd. of the United Kingdom states that tire temperature causes no significant change in noise level during drum tests of rib and lug bias ply truck tires between 25° and 125° F.

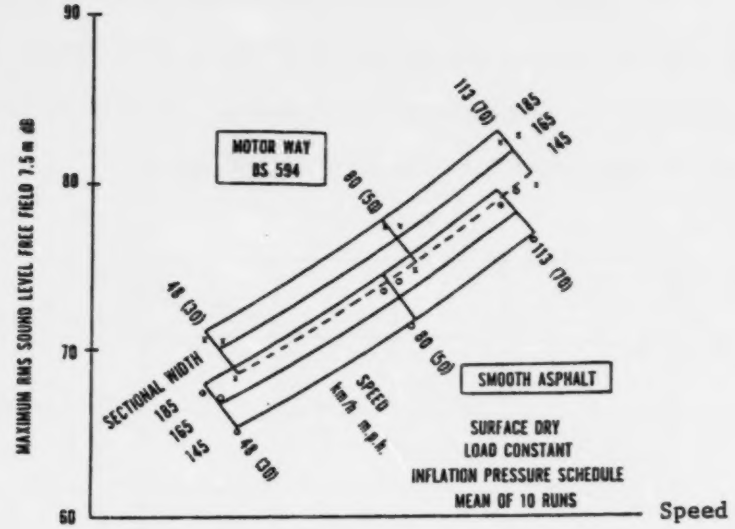
The only real effect of temperature that was highlighted is the initial noise from nylon tires that have been parked in cold areas overnight and have developed flat spots. This noise stops after the tires are driven for awhile and warm up to operating temperature. Both the Dunlop Ltd. (10) and French (41) studies mentioned this phenomen, but do not go into any detail on the nature of the tire construction.

4.C.3 Speed

4.C.3.A Noise Level

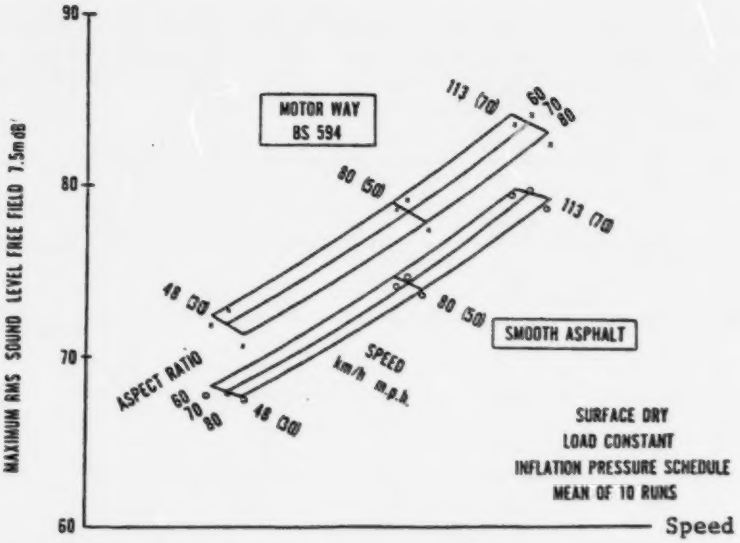
Speed appears to be one of the major influences on the level of noise emitted from tires. In 1977, Dunlop Ltd. of the United Kingdom reported (5) that with each doubling of speed, the noise level from tires increases 9-12 dB.

A study (10) issued in 1975 by Dunlop Inc. states that the noise level from truck tires shows an average 10 dB increase for each doubling of speed. This also corresponds to a 3 dB increase for each 25% increase in speed. The figures below from their report show an average increase of 9.5 dB for each doubling of speed for passenger car tires.



Lattice plot effect of sectional width, constant aspect ratio, 80 series 13 in serrated rib tyre. (10)

Figure 4-13



Lattice plot effect of aspect ratio, constant sectional width, 185 series 13-in serrated rib tyre. (10)

Figure 4-14

The figures below from Frietzche as cited in Urban Traffic and Noise (54) by Verband Der Automobilindustrie E. V. (VDA) of West Germany describe the same type of relationship - a 9-12 dB increase in car and truck tire noise for each doubling of speed.

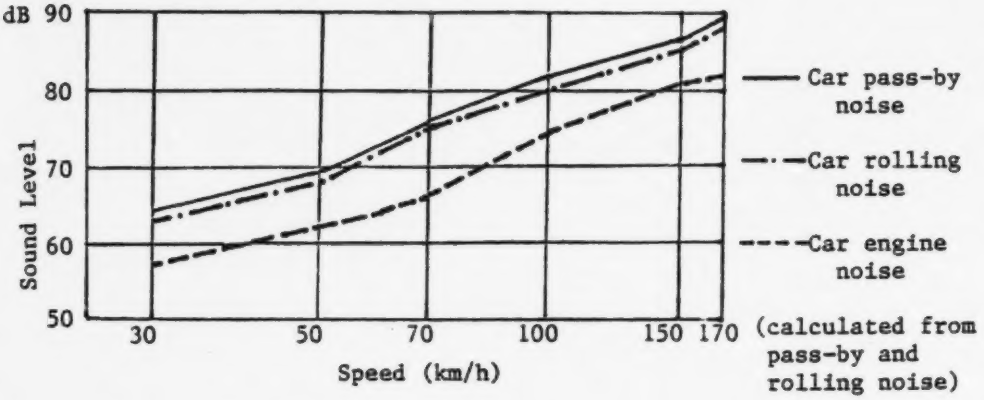


Figure 4-15

Sound level of car pass-by rolling noise (mean of 13 types) according to Frietzsche and calculated sound level of engine noise as a fundtion of speed. (Unaccelerated runs in direct gear on level road. Pass-by measurement with microphone at 7.5 m.) (54)

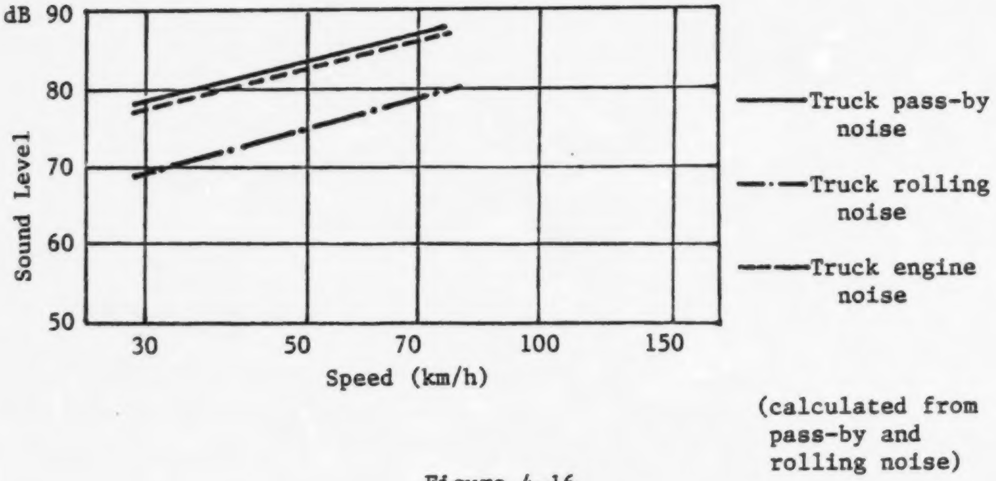


Figure 4-16

Sound level of truck pass-by and rolling noise, GVW 3.5t (mean of 11 trucks) according to Frietzsche and calculated sound level of engine noise as a function of speed. (Unaccelerated runs in direct gear on level road. Pass-by measurement with microphone at 7.5 m.) (54)

A 1974 study (41) by the Center for Evaluation and Research on Noise of the Institute of Transportation Research in France reported in part on measurements on tire noise from light vehicles. Their results, depicted in the figure below (from their report), also are in agreement with a 9-12 dB increase in noise level for each doubling of speed. Experimental French results also agree on 9-12 dB (104/3).

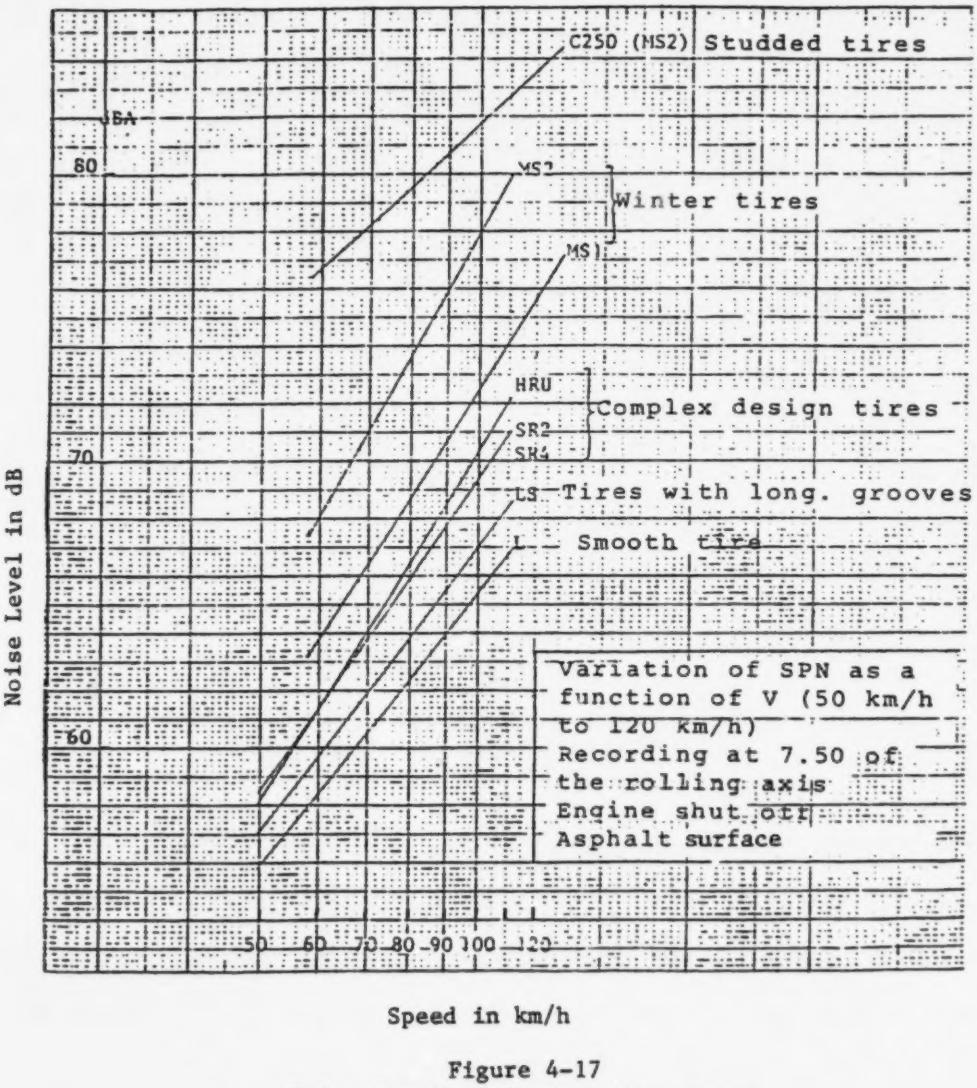


Figure 4-17
Noise Level of Various Tire Types
as a Function of Speed (41)

The figure below from a 1973 study (43) on truck/bus tire noise by the Japan Automobile Tire Manufacturer's Association, Inc. (JATMA) presents their findings as to the effect of speed on the level of noise from various types of tires.

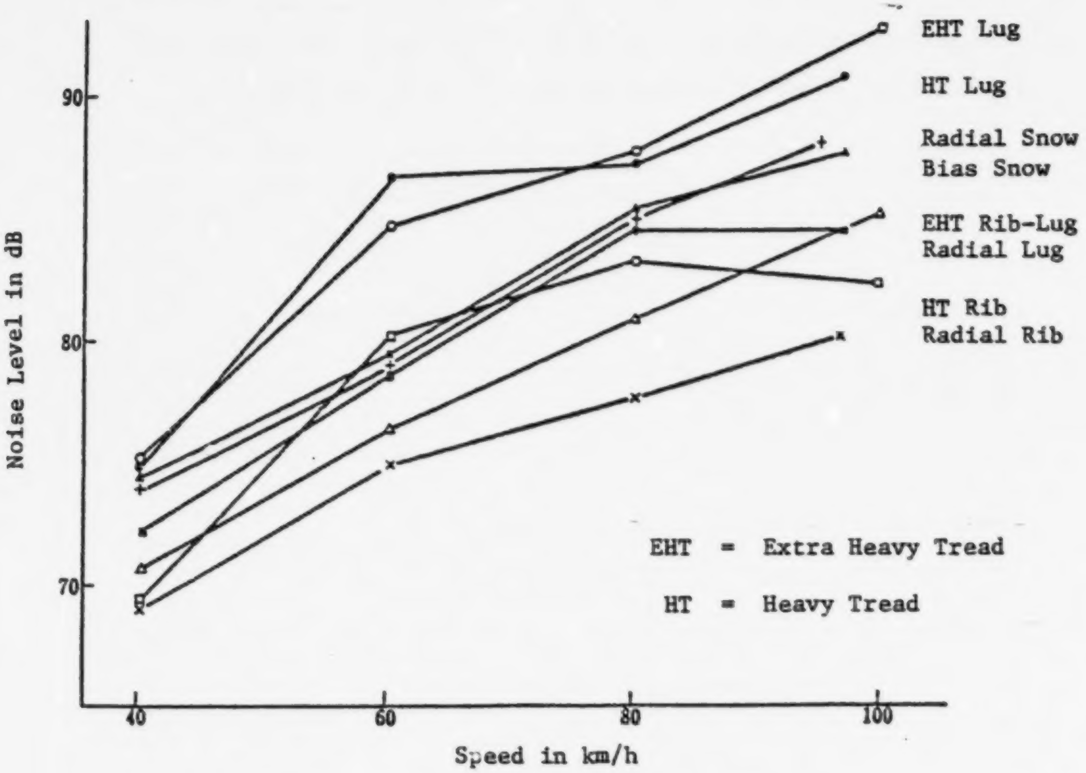


Figure 4-18

Effect of Speed on the Level of Noise
From Various Types of Tires (43)

Their results also fit the contention that tire noise increases 9-12 dB for each doubling of speed. The JATMA report states that as speed is increased, noise from rib tires increases less than does noise from lug tires. The following equations are given to explain the relationships:

For rib tires,

$y = 30.5 \log_{10}V + 24.1$

For lug tires,

$y = 41.6 \log_{10}V + 9.3$

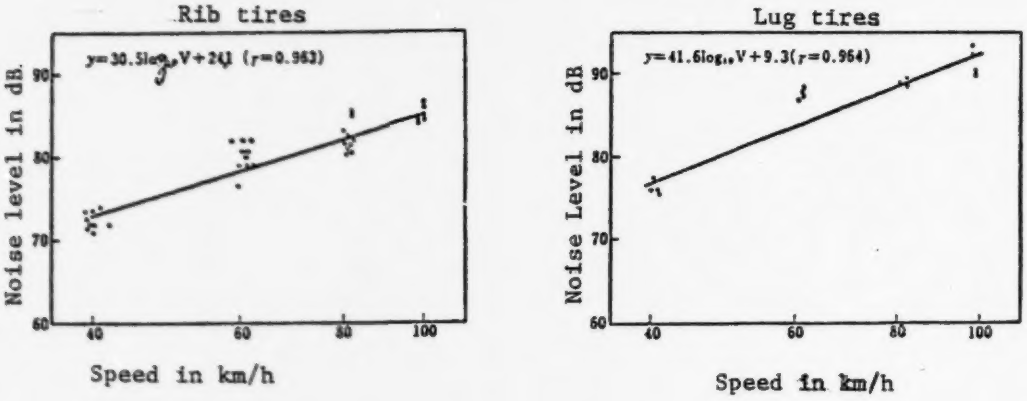
Where y = noise level in dB

v = velocity ($40 \text{ km/h} \leq V \leq 100 \text{ km/h}$)

load = 100% rated load

microphone distance = 7.5 m

The figures below from the JATMA report depict this situation where the noise from lug tires increases more rapidly with speed than does the noise from rib tires.



Where, load = 100% rated load
microphone distance = 7.5 m
surface = asphalt

Figure 4-19

Effect of Speed on the Noise From Rib and Lug Tires (43)

The JATMA report concludes that the noise level for general truck/bus tires is approximately 70-93 dB in the practical speed range of 40-100 km/h.

4.C.3.B Frequency

The 1974 study (41) by the Center for the Evaluation and Research on Noise of the Institute for Transportation Research in France (CERN) states that all "well treaded" tires emit noise at frequencies that vary linearly with speed. This is due to the periodicity of the discontinuities in tire/road contact. The figure below from the CERN study depicts this effect. It shows the frequency spectra of noise from a tire with a complex tread pattern at different speeds. A shift of the noise peak to higher frequencies can be seen as the speed increases.

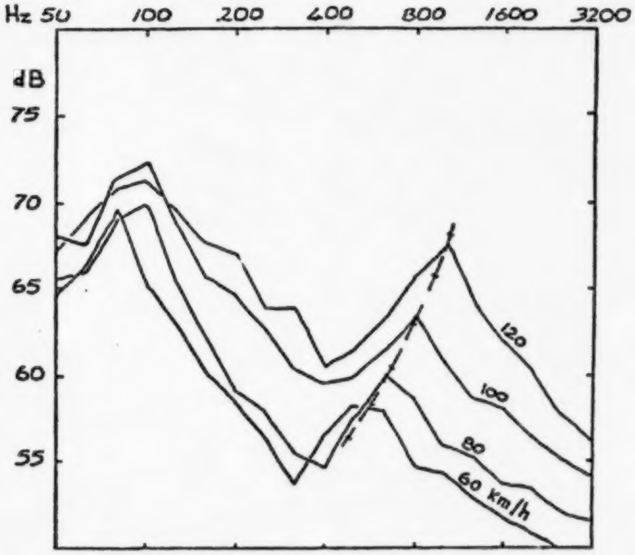


Figure 4-20

Effect of Speed on Frequency Spectra of Noise
From a "Well Treaded" Tire (41)

This same shift in peak frequencies with speed does not occur in tires with simple longitudinal grooves or ribs. The chart below from the CERN report of 1974 shows the frequency spectra of a tire with longitudinal grooves at different speeds. The peak for this tire occurs at approximately 1000 Hz for all speeds.

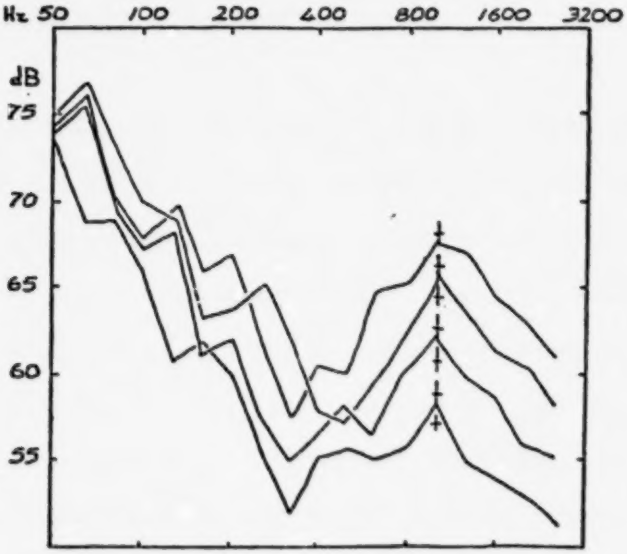


Figure 4-21

Effect of Speed on Frequency Spectra of Noise
From a Longitudinally Grooved Tire (41)

A study carried out under the auspices of the Motor Vehicle Noise Research Committee of the Japan Automobile Research Institute, Inc. (45) states that the predominant frequency of tire noise is due to the tread pattern, is dependent on speed, and can be explained by the following formula:

$$F = \frac{Vn}{3.6 \times 2 \pi r} \text{ Hz}$$

where F = dominant frequency in Hz

V = speed in km/h

n = number of grooves on the periphery of the tire

r = dynamic rotational radius of the tire in meters

For lug tires their measured frequency results agreed well with the results predicted by the formula. For rib and rib-lug tires, predominant frequencies were not as clearly visible but the measured results agreed with the predicted results in many cases. For radial tires predominant frequencies appeared at low speeds and the results corresponded to those predicted. At high speeds the results were unclear. For smooth tires, there were no predominant frequencies due to tread pattern.

A study issued in 1975 by the Japan Automobile Research Institute, Inc. (44) reiterates the forumula described in the previous study to explain the relationship between the dominant frequency in tire noise and vehicle speed. In addition, the report states that primary, secondary, and tertiary harmonics in tire noise shift to lower frequencies when speed is reduced.

As part of a study (35) reported in 1975, the Norwegian Road Research Laboratory looked at the effect of speed on the frequency distribution of tire noise. The report states that an increase in speed results in a general increase in the level of all frequency bands. However, they observed the largest increase in the frequency range of 1-2 kHz. The figure below from their report details their findings.

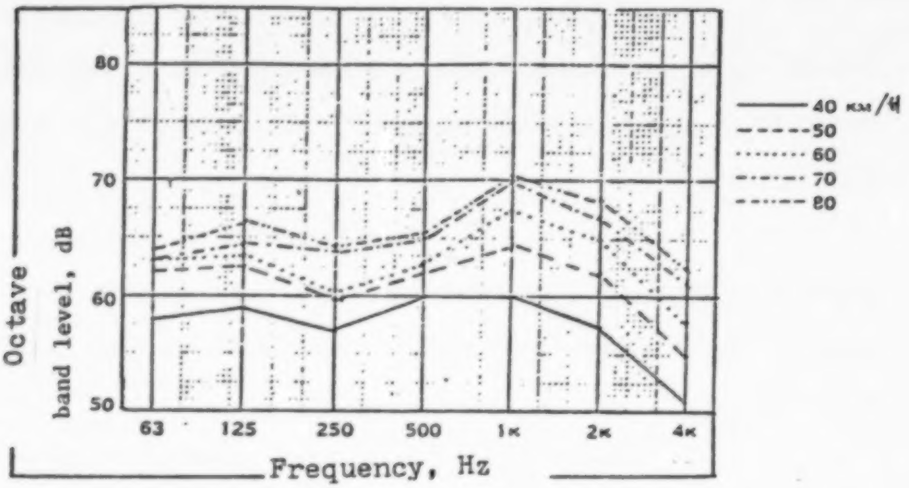


Figure 4-22

Effect of Speed on the Frequency Distribution of Tire Noise (35)

4.C.4 Load

In a study (41) reported in 1974 by the Center for the Evaluation and Research on Noise of the Institute of Transportation Research in France it is stated that the effect of increased load is to increase the contact area between the tire and road surface. Generally, whatever the road surface, the noise level is higher due to this increased contact. This is especially true for tires with pockets or transverse grooves. For heavy vehicles this noise increase can be as large as 8 dB.

A Japanese study by Sakagami et al. (47) states that for truck and bus lug tires, noise increases 6-7 dB when going from an unloaded to a fully loaded state. Noise from rib tires is essentially unaffected by cargo load. In addition, it was found that the peak frequency of tread pattern noise increases with increased load for lug tires but not for rib tires.

A 1977 study (57) by the University of Stuttgart in West Germany states that any change in the wheel load in a range that normally occurs in passenger cars has no significant influence on tire noise emission.

A 1975 Dunlop Ltd. study (10) cites Flanagan (Automotive Engineering April 1972) as reporting that if load is kept in the 75-100% range of the maximum rated load, the noise level will not change appreciably.

In 1974 the Transport and Road Research Laboratory of the United Kingdom issued a report (94) on "Rolling Noise and Vehicle Noise." As shown on the next page in Table 4- 2, data from this report indicates a typical increase in truck noise of 2-3 dB from unloaded state, for a variety of tires, surfaces and speeds.

In 1973 as part of a study (43) on truck/bus tire noise, the Japan Automobile Tire Manufacturer's Association, Inc. (JATMA) looked at the effect of increased load on the noise emitted from ten typical tires. The tire types considered were: Extra Heavy Tread lug, Extra Heavy Tread rib-lug, Heavy Tread lug, Heavy Tread rib, bias snow, radial lug, radial rib, radial snow, bias smooth, and bias straight-rib. The load was increased from 100% loaded to 150% overloaded. In general, they found that the effect of the increased load was small. The noise level increased slightly for lug tire patterns when the load was increased to 150% overload but this increase was smaller than increases found when the load was increased from unloaded to fully loaded conditions. The JATMA study also compared the noise spectra

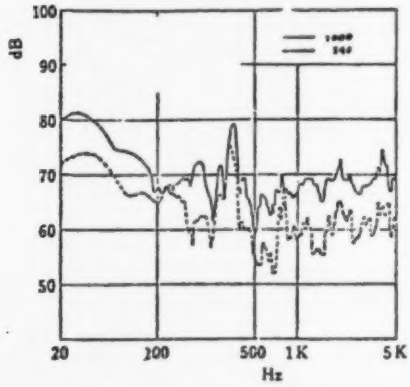
Table 4-2

Range of Coasting Sound Levels Measured in TRRL Investigations (94)

Vehicle	Mass Mg	Tires	Range of sound levels in dB for a speed range of 50-100 m/h Surface dressed with coated chips (dry)	Hot rolled asphalt (dry)
Lorry (6 wheel rigid)	5.6	Smooth natural rubber	67-76	68-79
"	13.2	Smooth natural rubber	69-78	72-81
"	5.6	7 circumferential ribs, natural rubber	67-78	70-80
"	13.2	7 circumferential ribs, natural rubber	69-78	73-83
"	5.6	5 circumferential ribs, natural rubber	68-78	71-83
"	13.2	5 circumferential ribs, natural rubber	70-80	72-83
"	5.6	Transverse grooves natural rubber	70-80	72-83
"	13.2	Transverse grooves natural rubber	72-83	74-86

of the tires in the two loading conditions and found no fundamental differences. Figure 4-23 from the JATMA report, on the following page, details their results concerning the noise levels from different types of tires in 100% and 150% loaded conditions.

In a study (44) reported in 1975 the Japan Automobile Research Institute, Inc. (JARI) briefly addressed the question of the effect of load on truck tire noise. Their report states that noise from rib tires is hardly affected by changes in load but that lug tire noise increases greatly with an increase in load. The figure below from the JARI report depicts their findings as to the variations in sound pressure level of a tire with a single groove as the load is changed. It can be seen that as the load is increased the noise level also increases.



Where, speed = 100 km/h and load is in kg

Figure 4-24

Variations in Sound Pressure Level of a Tire
With a Single Groove as the Load is Changed (44)

The Federal Institute for Street Systems in West Germany

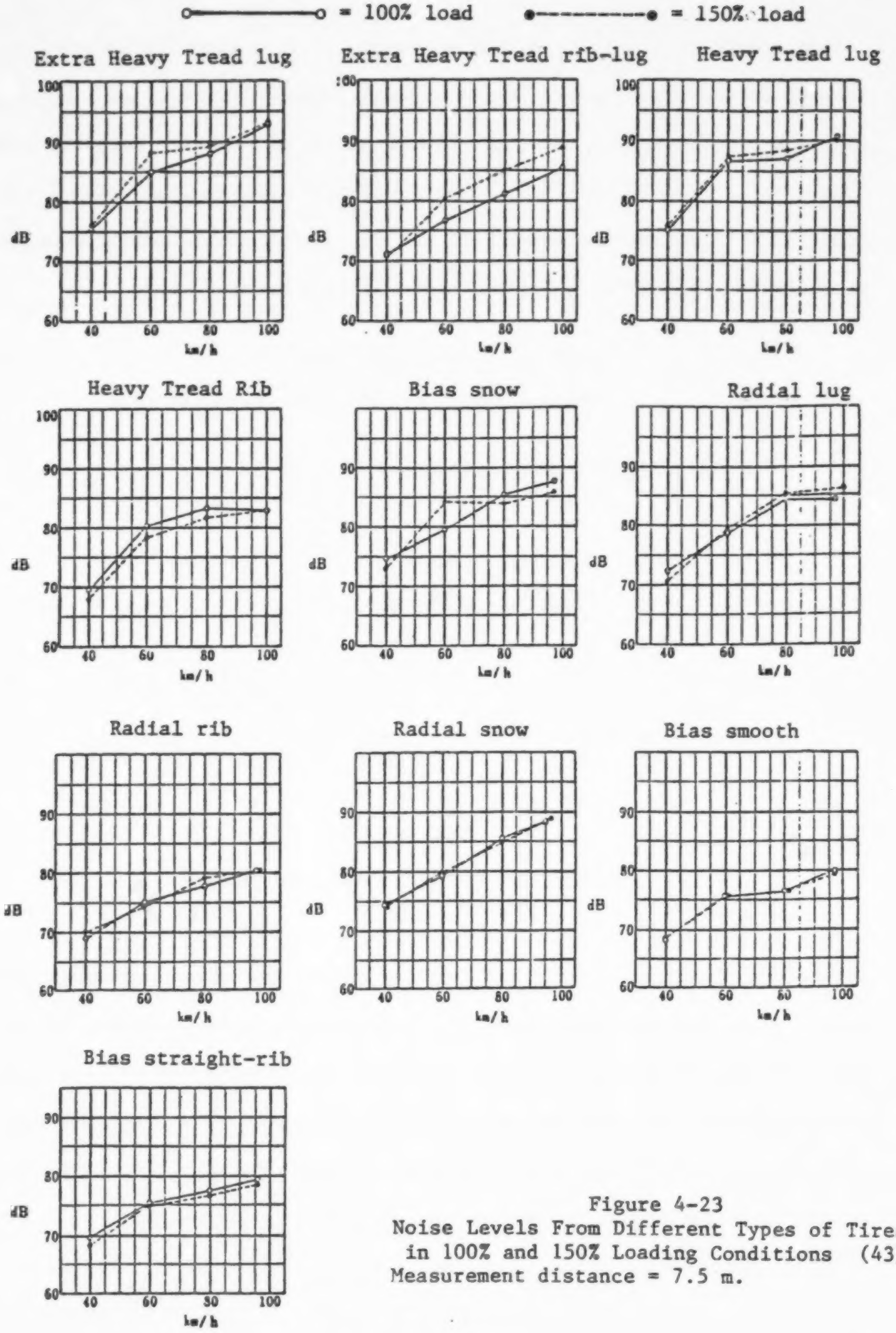


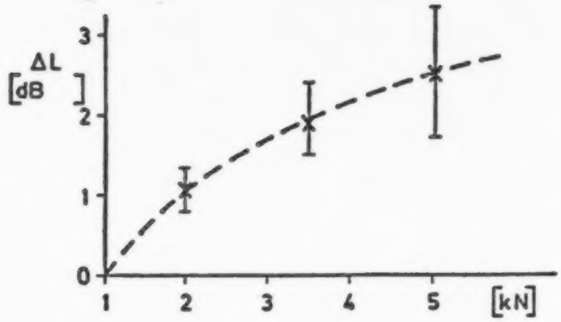
Figure 4-23
Noise Levels From Different Types of Tires
in 100% and 150% Loading Conditions (43)
Measurement distance = 7.5 m.

issued a report (38) in 1978 that addressed the relationship between car tire noise and wheel load. Their research looked at five tires (two summer tires, one mud and snow tire, and two blank tires) at 100km/h and at load levels of 1, 2, 3.5, and 5 kN*. They found that tire rolling noise levels increase with increasing wheel load and state that the following equation explains the relationship between noise level and wheel load:

$$L \sim 3.6 \log (\text{wheel load})$$

where L = noise level, (units not given).

The figure below summarizes the results from their report:



Where, kN ≈ 102 kg

Figure 4-25

The Relationship Between Tire Noise
and Wheel Load (38)

The Federal Institute for Street Systems states that the increase in noise level due to the increased wheel load could possibly be explained by the increased tire/road contact area. However, this does not provide a complete explanation because when the wheel load is increased from 1 kN to 3.5 kN the noise levels of all five tires increased by approximately 2 dB while the contact area increased in amounts that varied from 10% to 100%.

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* 1 kilo Newton = 1,000 Newtons = 224.8 lb.

4.C.5 Other Operating Factors

There are several other factors that can affect the level of noise emitted by a tire. Examples of these factors are irregularities in the shape of the tire, defects, non-uniform peripheral hardness, and unbalanced wheels. A report (42) issued in 1971 by the Traffic Environment Research Section of the Ministry of Construction of Japan states that these factors can generate exciting forces in the tire that generate the same sound as road noise.

A French study of tires mounted on a vehicle on rollers in an indoor environment suggests that "toe-in" may be a factor in noise emissions. A toe-in of 3 degrees resulted in an increase in noise of 15 dB (104/3). No data are known for actual operating conditions, however.

4.D General Tire Research

Two research projects (30) are underway in Sweden that could provide valuable information on the effects of tread patterns on tire noise. Unfortunately little information is currently available to describe these projects. Both are being conducted by IFM-Akustikbyraan AB. One project was started in January of 1978 and it was estimated that it would be completed in January of 1979. It is an attempt to develop methods for the characterization of tires with respect to tire noise. The other project began in November of 1976 and it is estimated that it will be completed in November of 1980. This project is attempting to develop tires and road surfaces that create less rolling noise.

5. INFLUENCE OF THE ROAD SURFACE

5.A Introduction

Noise actually depends on both parts of the tire/road interface and the complex interactions which occur between them. Thus, various tire/road combinations will be discussed here. Since tread has already been discussed separately, a useful way of handling the variables will be to settle on a few basic types of tread and, for each, examine how the noise varies as the road surface is changed. The most common types of tread are:

CAR
- o straight rib
- o patterned rib, including the "block" patterns on radial tires as an extreme pattern, as shown in Figure 5-5
- o snow tires
- o studded snow tires

The first two are frequently called summer tires, the last two, winter tires.

TRUCK
- o straight rib
- o cross lug

In the first sections only dry surfaces will be dealt with. See Section 5.E for noise increases due to wet surfaces. For cars, the effects of tire size and construction (bias, radial), load and tread wear will be neglected, since they are less than 1-2 dB (Ref. 9). For truck tires, however, the effect of load and tire wear can be significant (4-8 dB), and therefore must be specified.

5.A.1 Specifications of Road Surfaces

There is no one satisfactory method of uniformly describing the essential characteristics of road surfaces. There are descriptive terms such as "brushed concrete" or "smooth bituminous," which vary from country to country. These are practically useless for comparative purposes (103/14). Then there are some named by the country specs, such as the English "BS 574," which may be more consistent from place to place. If there is aggregate (stones) in the road surface, their size and whether they are precoated (with asphalt) are frequently mentioned. Finally, an approach for describing surface roughness has been developed using the concepts of macrotexture and microtexture. Macrotexture pertains to features on the order of 0.1 to 10 mm. Roads need macrotexture to help clear surface water away from the tire/road contact patch. One measure of macrotexture is "texture depth," which is calculated from the area of road required to absorb a fixed volume of test sand. Grooving is one method of adding macrotexture to the road, in which case a "groove equivalent texture depth" can be calculated from the cross-sectional area of the groove and the average distance between grooves. Depending on the type of grading (mix), wear (age), and size of stone chips embedded in it, each surface material is capable of being laid in a range of texture depths.

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*Ref. No. 13, p. 14

For example, in one South African study, the ranges were as follows:

Material	Texture Depth
Asphaltic concrete	.1 to .6
Gap graded asphalt	.4 to 1.5
Open graded asphalt	.6 to 1.8
Surface treatments	.7 to 2.0

Sandberg of Sweeden has suggested a standard way of reporting surface texture (Table 5-1). The wide variety of names in use for what are probably the same types of surfaces can be seen in Table 5-2 (p. 5-5).

Another useful way of characterizing surfaces is by their braking friction coefficients (BFCs), defined as the ratio of braking force to normal load on the wheel. The higher the BFC, the greater the skid resistance. Either peak or sliding BFCs can be measured. In all cases the peak BFC is much higher than the sliding BFC. It is not accurate to ascribe to any road surface a particular braking force coefficient. BFCs vary with the particular tire/surface combination, and vehicle speed, as shown in Figure 5-1. BFC measurements also vary with road wetness. Gripping is reduced when surfaces are wet, so the wet-gripping coefficient is considered the more critical.

Standard BFC test methods have been developed. The British standard method uses the Sideway Force Coefficient Routing Investigation Machine (S.C.R.I.M.). In this machine, the sliding lateral force coefficient of a blank tread motorcycle tire at a slip angle of 20° is measured in the wet at a speed of 50 km/h (31 mph) (5/243). The resulting BFC numbers are sometimes also called SFCs (Sideway Force Coefficient of

Height of asperities * (2·texture depth) mm	Air permea-bility**	Micro-roughness	Period (wave-length) of roughness, lon-gitudinally mm	Degree of periodicity	Period (wave-length) of roughness, transversally mm	Degree of periodicity
0 - 0,5 0	Small 0	Smooth 0 (polished)	0 - 1 0	Weak 0	0 - 1 0	Weak 0
0,5 - 1 1	Medium 1	Medium 1	1 - 2 1	Distinct 1	1 - 2 1	Distinct 1
1 - 2 2	High 2	Harsh 2 (unpolished)	2 - 4 2	Pronounced 2	2 - 4 2	Pronounced 2
2 - 4 3			4 - 8 3		4 - 8 3	
4 - 8 4			8 - 16 4		8 - 16 4	
8 - 16 5			16 - 32 5		16 - 32 5	
16 - 6			32 - 64 6		32 - 64 6	
			64 - 128 7		64 - 128 7	
			128 - 256 8		128 - 256 8	
			Random R		Random R	

* Estimation of peak-to-peak-value. Can be substituted by (texture depth)·2 measured by the sand patch method.

** Here: The capability of the pavement to remove air enclosed in the contact patch between tire and road; drainage through the surface as well as between the tire contact patch and the road surface.

TABLE 5-1

Swedish Proposal for Specifying Road Surface

(Ref. 33/15)

TABLE 5-2
A CATALOGUE OF SELECTED ROAD SURFACES OF VARIOUS COUNTRIES

Ref. No.	Surface No. In Ref.	Country	Their Description	Their Comments	Wet BFC at 80 kph***	Texture Depth (mm)	Macro-texture (rough-ness)	Micro-texture (harsh-ness)	Grooving	New/Worn (Blank = not given)
57A	1	W. Germany	Bituminous Sludge	Special test section	0.10	0.14	Smooth	Smooth	Yes	
"	2	"	Worn concrete	Federal road	0.34	1.52				Worn
"	3	"	Relative new asphalt concrete	Country road	0.29	0.24				Worn
"	4	"	New asphalt concrete with slight splitting	Federal road Federal road	0.31 0.31	0.39 0.39				New New
"	5	"	Granite pavement		0.38					
"	6	"	Asphalt concrete with mean roughness		0.36	0.31	Medium*			
"	7	"	Asphalt concrete with mean roughness		0.34	0.33	Medium*			Worn
"	8	"	Asphalt concrete of great roughness	Country roads	0.38	0.56	V. rough*			
"	9	"	Asphalt concrete of great roughness		0.39	0.47	V. rough*			
"	10	"	Asphalt concrete of great roughness		0.40	0.52	V. rough*			
"	11	"	Red mastic	Park surface	0.49	1.13				
"	12	"	Asphalt concrete, fine-grained, very rough		0.49	0.59				Worn
"	13	"	Asphalt concrete, rough grained, very rough	Much-travelled test sections	0.52	0.90	V. rough*			Worn
"	14	"	Asphalt concrete, large grained, very rough		0.48	0.59	V. rough*			Worn
"	15	"	Asphalt concrete, large grained, very rough		0.51	0.51	V. rough*			Worn
97		Australia	Smooth asphaltic concrete			0.09	Smooth*	Smooth		
"		"	Chip seal surface - very coarse			3.64	Rough	Rough		
"		"	Chip seal surface - reg. coarse			2.54	Medium			

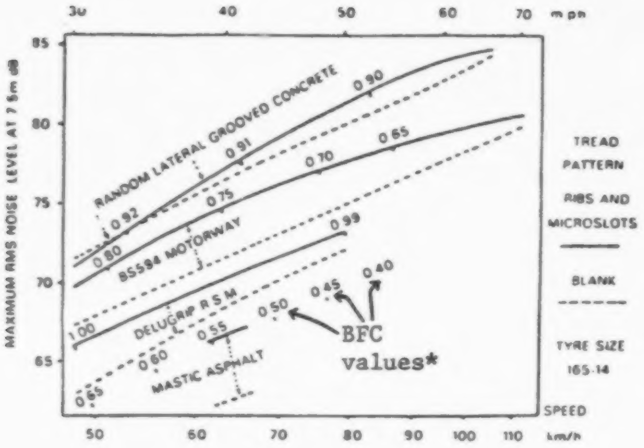
* As characterized in the reference.
** Using an English test method.
*** Using standard treaded tire (Stuttgart Friction meter)

TABLE 5-2
A CATALOGUE OF SELECTED ROAD SURFACES OF VARIOUS COUNTRIES

Ref. No.	Surface No. In Ref.	Country	Their Description	Their Comments	Wet BFC at 80 kph***	Texture Depth (mm)	Macro-texture (rough-ness)	Micro-texture (harsh-ness)	Grooving	New/Worn (Blank = not given)
5		England	Random lateral grooved concrete		*0.91**		Rough		Yes	
5,10		"	BS 594 Motorway (hot rolled asphalt with precoated chips)		*0.68		Medium			
5,10		"	Delugrip RSM		*0.99					
5		"	Mastic asphalt (smooth skidding test track surface)		*0.43		Smooth	Smooth		
10		"	Smooth asphalt sand carpet							
5/243		"	Lateral brushed concrete (marks 1-2½ mm deep, 3-10 mm apart)				Rough			
5/243		"	Random lateral grooved (grooves 10 mm wide, 30-50 mm apart)						Yes	
Mills-70		"	Smooth tar macadam				Smooth	Smooth		
10		"	Coarse granite							
5/187		"	Friction coarse							
100	1	S. Africa	13 mm single seal (Quartzite)	Good	0.43	2.8				1 Year
	2	"	13 mm + 7 mm double Seal (Quartzite)	Good	0.45	1.7				1 Year
	3	"	13 mm + 7 mm double Seal (Quartzite)	Good	0.32	1.0				3 Years
	4	"	Gap-graded asphalt + prec. chips (Quartzite)	Good	0.35	1.2				1 Year
	5	"	Gap-graded asphalt + prec. chips (Quartzite)	Smooth	0.17	0.4				1 Year
	6	"	Gap-graded asphalt without prec. chips (Dolerite)	Smooth	0.14	-				1 Year

Ref. No.	Surface No. In Ref.	Country	Their Description	Their Comments	Wet BFC at 80 kph***	Texture Depth (mm)	Macro-texture (rough-ness)	Micro_texture (harsh-ness)	Grooving	New/Worn (Blank = not given)
	7	"	Asphaltic Concrete (Norite)	Unused	0.29	0.6				3 Years
	8	"	Asphaltic Concrete (Norite)	Smooth	0.18	0.13				3 Years
	9	"	Asphaltic Concrete (Norite)	Smooth	0.25	0.4				3 Years
	10	"	Open-graded asphalt (Quartzite)	Good	0.43	1.6				1 Year
	11	"	Open-graded asphalt (Quartzite)	Good	0.39	0.1				1 Year
	12	"	Open-graded asphalt (Quartzite)	Good	0.38	1.1				1 Year
	13	"	19 mm stone + slurry Seal (Quartzite)	Good	0.29	0.6				1 Year
	14	"	19 mm stone + slurry	Good	0.26	0.5				1 Year

friction). (100/4-3)



*Peak wet BFC values

Figure 5-1

External car coasting noise generation on dissimilar dry surfaces with blank and patterned tires. (5/244, Fig. 4)

In German experiments, the standard measurement used for the last two decades has been the stuttgart friction meter. This method uses a standard (treaded) locked and sliding tire. This method works according to a standardized measuring method which was worked out by the Working Committee for "street traction" of the Research Society for Street Systems. It determines the test conditions which are to be adhered to with friction measurements under wet conditions (gripping capacity measurements). These are defined as follows:

- Constant driving speed;

  v = 20, 40, 60, 80, 100 km/h

- Standard tires with tread:

  Phoenix P3, size 6.40-13[1]

- Standard tires with tread:

  Phoenix P3, size 6.40-13[1]

- Tire air excess pressure:

  $p = 1.5$ atm

- Wheel load:

  $F_{GR} = 3434$ N

- Roadway wetness:

  with a water film of a computed thickness of
  1 mm at all speeds

- Dirtiness of the roadway:

  None

- Slip of the measuring wheel:

  100% (blocked braking)

The thus ascertained slip coefficient of the blocked standard wheel is designed here as $_{\text{G standard 1}}$ and serves as a measuring magnitude for roadway gripping capacity. It is the ratio of the frictional force F_R (between tire and roadway determined under the named conditions) and wheel load F_{GR}: $\mu_{\text{G standard 1}} = F_R / F_{GR}$

A rough correlation exists between the BFCs measured in different ways. (100/4-3)

Nelson considers it also important to know the range of wet BFCs over the range of driving speeds, since the wet BFCs tend to become smaller at higher speeds, posing a safety problem (98). Table 5-2 attempts to identify some road surfaces by the name used locally, description in terms of structure, description of terms of macrotexture and microtexture, and wet BFCs.

5.A.2 Uneven Wear in Actual Roads

In actual roads, the surface varies across the road because of two strips of maximum wear worn in each lane by vehicular traffic. Thus, it was possible for Canadian researchers to measure the noise from two types of road surface using one road, simply by having the car coast by on a path offset from the usual one by several feet. The noise effect was a change of ± 1 dB (12).

5.A.3 Degree of Overall Wear

A Norwegian team measured the same roads twice: once when new and once after six months of wear including much traffic using studded tires. The macrotexture had been roughened enough to increase the noise level by 2.5-3 dB for three surfaces: two aggregate and one smooth asphalt for patterned rib tires at 70 km/h. The fourth surface, "surface treatment," had stones sticking up that had been worn off by the studded tires, thus becoming smoother than when new, and the noise level decreased by 1.5 dB (35/19). However, it is safe to say that most surfaces become rougher when worn by studs, so the noise goes up. Conversely, as textured concretes wear, they become smoother, so the noise level (and the traction) tend to go down.

5.A.4 Type of Noise Measurements

Pass-by and close-in measurements will be the only types used in this section. Lab-drum measurements may not be transferable because of problems such as getting representative surfaces to adhere to the drum, and the curvature of the drum.

5.B Effect of Road Surface for the Case of Passenger Cars

5.B.1 Introduction

The noise of a blank (smooth) tire is lowest on the smoothest surfaces and increases with surface roughness. The noise of a treaded tire is higher than the blank on the smoothest surface and increases with surface roughness. According to one theory, at some roughness the blank becomes noisier than the treaded tire (Figure 5-2).

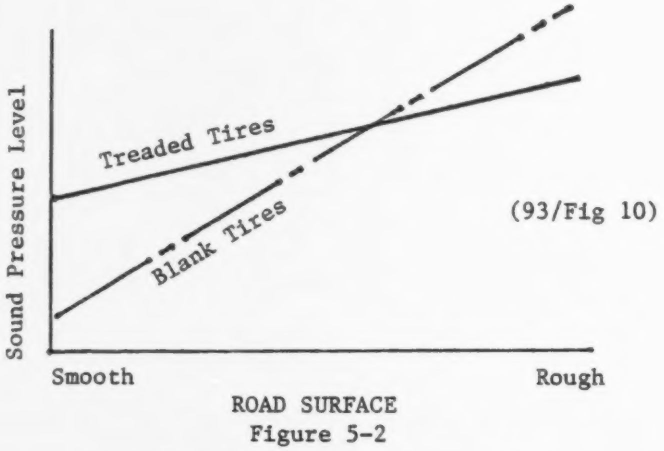


Figure 5-2

Idealized Version of Relationship
Between Noise Level and Road Roughness

The report containing this theory (93) does not indicate whether this phenomenon occurs at all velocities of normal interest (e.g. 40 km/h to 120 km/h), or whether there is some upper limit of roughness wehre the relationship no longer holds.

5.B.2 Results of Studies

A German study (Essers, 1978, Ref. 53 and 53A) does not completely bear out the Austrian theory. The Figure 5-3 shows the complete data on ten production tires and 4 blank test tires on 11 surfaces of varying roughness. In Figure 5-4 we simplify the data to show key points. On the y axis is noise level measured by a close-in microphone; on the x axis are the surfaces in order of increasing wet braking friction coefficients. The number of surfaces has been reduced to one very smooth plus four concretes differing only in surface roughness; the rougher concretes have higher BFCs in this case.

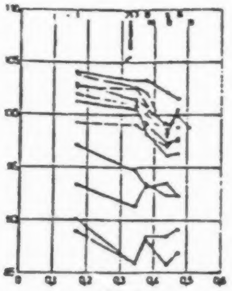
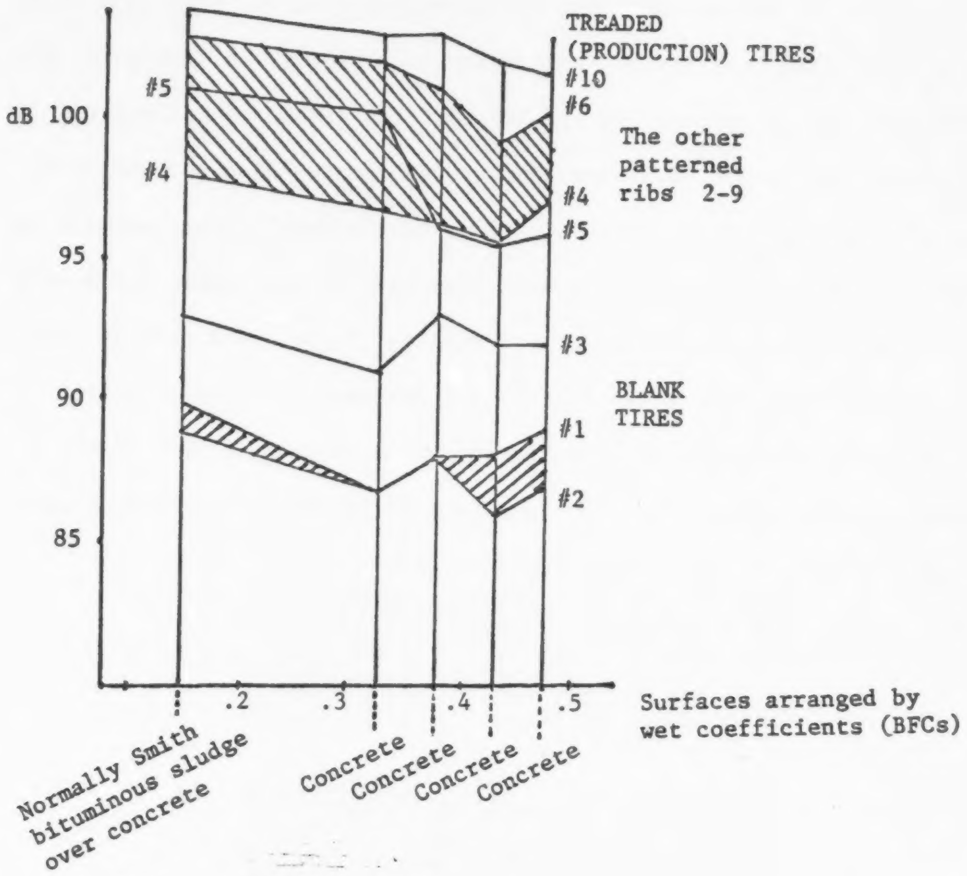


Figure 5-3

Noise vs. Roughness as Measured by BFC for Various Tires.
Source: Ref. 53, p. 21



CAR V = 80 kph DRY

Tire 01-02--Blank tires of two different widths

Tire 03--blank with 2 grooves cut to make primative rib

Tire #4-#5--The quietest patterned rib

Tires #6--Zig-zag tread tire noisiest patterned rib

Tire #10--Block tread (snow tire

Figure 5-4

Simplified Version of Figure 5-3

It can be seen that on the smooth surface, the blank tires are quieter than the treaded production tires by 8-14 dB. However, the noise does not go up much (if at all) with the rougher surfaces, nor do the lines for treaded vs. blank tend to intersect. Also noteworthy is that the snow tire (#10) is noisier than the "summer" tires, but not by much. A possible reason is the fact that many of the summer tires have a blocking pattern resembling the snow tire. To be noted also is that the most rib-like treads (#4 and #5) are the quietest, and a zig-zag pattern (#6) is the noisiest of the summer tires (Fig. 5-5). There appears to be a consistent 4-6 dB difference between the noisiest and quietest summer treads, regardless of surface.

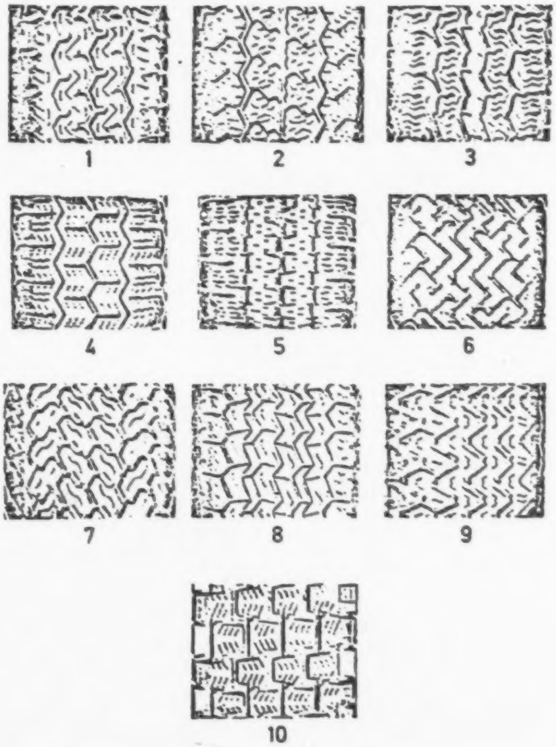
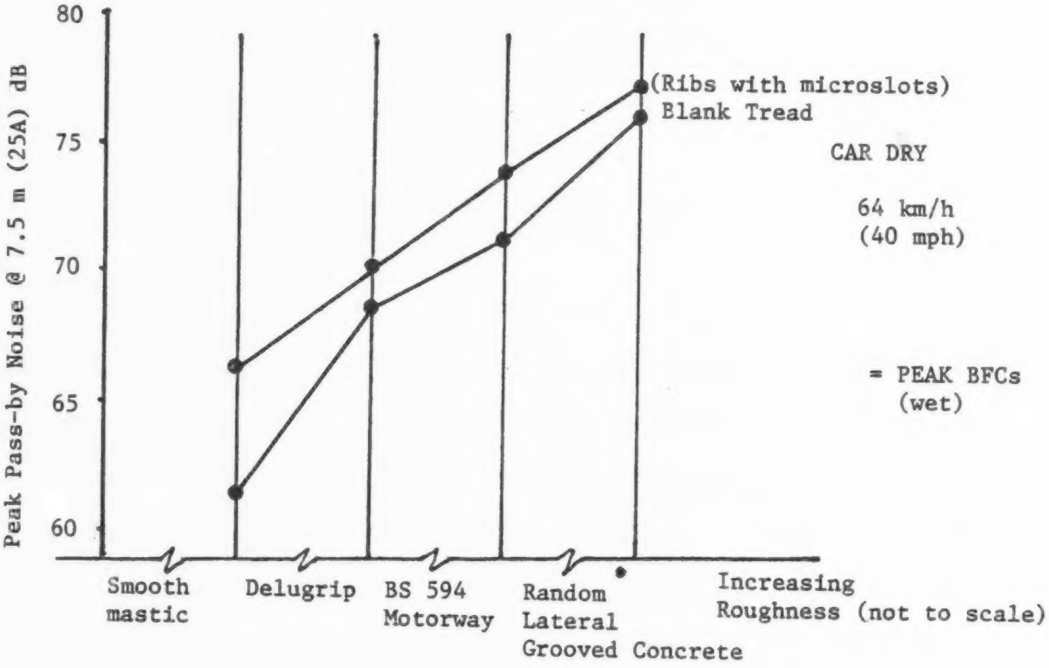


Figure 5-5

Pictures of the Production Tire
Treads Used in the Essers Study (53/18)

The results of the Esser study are inconclusive. One apparent difficulty is that the four concrete surfaces, while obviously of different macrotexture, might be rank-ordered in terms of roughness one way by one measure (BFC) and yet have a different rank order by another measure (e.g. texture depth).

An English study also casts doubt on the existence of a "cross-over point" with increasing roughness, after which blank tires are noisier than treaded ones. The four surfaces shown in Figure 5-6 span the range from smoothest to roughest surfaces, but the treaded tire (rib) is always noisier.



(5/244. Data extracted from Figure 5-1 of this report.)

Figure 5-6

Noise vs. Road Surface Roughness,
Blank Tread and Rib Tread

5.B.3 Maximum Effects of the Surface

The preceding data make it likely that in general, the noise "floor" for passenger car tires is established by blank tires on a very smooth surface. Also, for any rougher surface, it is likely that the "floor" continues to be established by the blank tire. Then what is the maximum effect of the surface for any kind of surface and any kind of passenger tire (except studded snow tires)?

Figure 5-4 suggests it to be 14 dB. Ullrich found it to be 13 dB, based on calculations from hundreds of pass-bys of actual traffic (37/5-7).

Cross-grooved concrete	13 dB	4 dB	10 dB All practical surfaces in actual use
All ungrooved surfaces used at present time		6 dB	
The smoothest test surfaces; not used on actual roads		3 dB	

The range of 10 dB for all surfaces in use is confirmed by the Canadian, Hajck (9). If cross-grooved surfaces are excluded, the range for all other in-use surfaces is about 6 dB, which is confirmed by another Ullricht study for new concretes only (4-5 dB) an Austrian study (5 dB), and a French study (6 dB) (all referenced in 37A/5), a South African study (100/4-10), and a Swedish study (101/6), both 6 dB.

5.B.4 Noise vs. Texture Depth

Figure 5-7 shows German results for a blank tire. The scatter shows that texture depth, which is associated with vibration, is not likely to be completely explanative. Other mechanisms (micro-snubbing?, air pumping?) not directly limited to texture depth may also play a role. A Danish study shows similar scatter in the noise vs. texture depth relationship. (102/11)

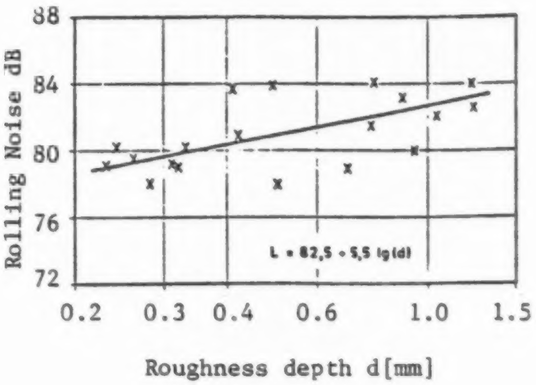


Figure 5-7

Rolling noise level of a test vehicle with a treaded tire at 100 km/h as a function of the roughness depth of different concrete surfaces (measured with the sand surface method) (37A/9) (measurement distance not specified)

Noise Increase Per Doubling of Roughness
(macrotexture as measured by texture depth)

Tread Type	Country of Study	Noise Level Increase by Doubling of Roughness (dB)	Range of Texture Depth Range (mm)	Logarithmic Relationship if Given
Blanks	West Germany	3.3	.3 to 1.2	L 5.5 log d
Not Given	France	3.5	.3 to 3.0	L 6 log d
" "	United States	5.5		L 9 log d
" "	England	4.5 concrete		L 7.4 log d
		2.3 asphalt		L 3.8 log d
Michelin 185 HR 14x5V-P Radial (Summer) (patterned rib)	Denmark	2	.1 to .4	not given

Table 5-3

Noise Increase with Surface Roughness
As Measured by Texture Depth

Ref. 37A/9-10; Danish data: 102/11

The wide variation indicates that other parameters are also important. Two parameters may be tread type and whether the road surface is asphalt or cement (see the listing for the English study in Table 5-3). At best, noise is probably roughly proportional to texture depth up to about 1.0 mm.

Some Swiss, French and Japanese data on noise vs. texture depth has been brought together in a Swiss study (Figure 5-8).

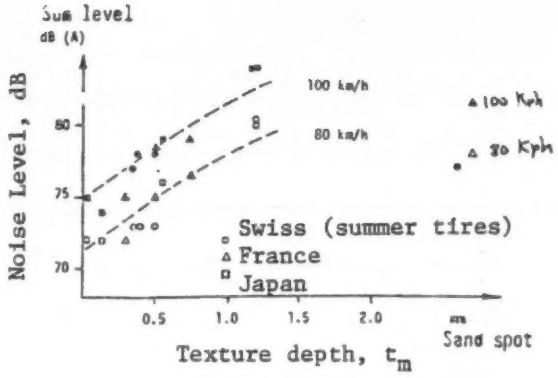


Figure 5-8

Rolling Noise Development as a Function
of Mean Texture Depth (measurement distance
not specified).

But when the texture depth is much over 1 mm. the relationship may start to break down, possibly because of increased sound absorption from the deep cavities in a very porous surface. As it is explained in the Swiss study:

> Generally, with increasing texture depth, the sound absorption also increases due to the pavement surface. The pavement with surface treatment (5), with a texture depth of 2.6 mm and a dimension of rolling noise development corresponding with that of pavements with texture depths of 0.5 mm shows clearly that the mean texture depth starting with about 1.0 mm is no longer the only criterion for the absolute extent of rolling noise development.

5.B.5 Noise vs. Surface Material

For the most typical passenger tire (patterned rib) at freeway speeds, both a South African and a Swedish study indicated that "open graded" asphalt was the quietest surface, as measured in a pass-by test at 7.5 m. The Swedish measurements were made at 90 km/h; the South African, at 130 and 70 km/h. For all three speeds the rank order of surfaces remained the same:

open-graded asphalt	quietest
asphaltic concrete	3-4 dB noisier
surface treatment ("surface dressing")	5½-6½ dB noisier

(100/4-10; 101/6)

The fact that "surface" dressing is a potentially noisier surface in combination with passenger tires than other typical surfaces is confirmed by a Danish study, where it was about 6 dB noisier than "drainage asphalt," even though both had the same texture depth (0.4 mm) (102/11).

5.C Effect of Road Surface on Truck Tire Noise

5.C.1 Overview

Evidently truck tires are not as sensitive to change in road surfaces as are passenger car tires. Moreover, the smoothest road surface, as defined by small texture depth, is not the quietest. The effect of surface seems more complex.

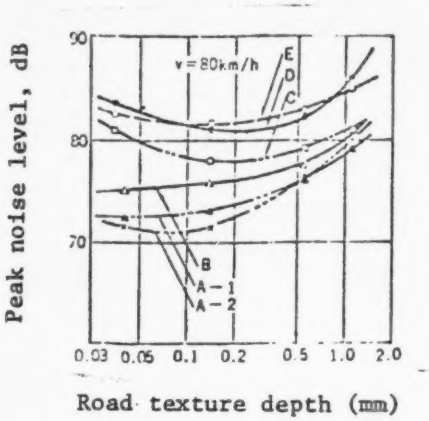
No.	Roughness	Surface	Blank	Tire Tread Types Avg. of 2 rib treads	Traction (lug tread)
1.	Smooth	Smooth concrete polished concrete	73	79	88
2.	Med. rough	Coarse Quartzite macadam with 9 mm stones	78	79	82
3.	Rough	Motorway rolled asphalt with 19 mm stones	81	83	86
		(Change from #1 to #3)	8dB	(4 dB)	(-2)

Loaded truck,
coast-by at
15 m, 100 km/h

TABLE 5-4

Truck tire noise for various tire/road combinations
(Ref. 10/185)

A Japanese study used only rib tires on a t ton truck, and on a 20 passenger bus and a 50 passenger bus as well, but specified the road surfaces much more precisely in terms of texture depth. As texture depth increased, noise first decreased then increased, forming a "U-shaped curve" for the heavy vehicles (Figure 5-9).



A-1	Cars
A-2	Cars
B	Minibus
C	20-passenger bus
D	Heavy truck
E	50-passenger bus

Figure 5-9

Vehicle Noise vs. Coarseness of the Road Surfaces, for Light and Heavy Vehicles

Surface textures producing a minimum noise were in the 0.1 - 0.3 mm texture depth range (curves C-E). Meanwhile, the curves for the light vehicles (A-B) are not dissimilar from those already presented for cars in the previous section--increasing noise with increasing roughness, at least through (texture depth = 1.0 mm), and no inflection point in the curve, (not even for curve A-2, where the line is not well drawn given the data points).

Another researcher is uncertain that there is any correlation at all for trucks between noise and texture depth, although he found one for light behicles (10, 91, 98).

The range in noise for different pavements (at 10-90 km/h) was 8-15 dB in one study (94/2), for a range of treads. For one truck going over nine pavements at various speeds, it was about 8 dB.

Truck tires don't behave as regularly as car tires with respect to surface Perhaps it is because the effect of the "aggressive" tread, perhaps because the different size of the tire leads to other noise generation mechanisms.

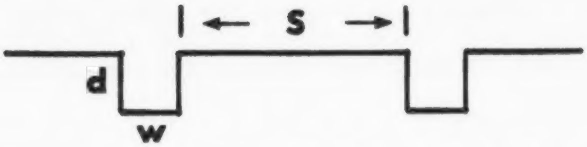
5.D Effect of Cross-grooving

Grooving is a special case of artificial macrotexture added to the surface of the road to improve its traction or gripping quality. It is usually applied to concretes, which are fine grained and dense substances whose surface, if originally "broom textured", may tend to wear smooth with time (36/ii). It does not seem to be applied to asphalt or bituminous surfaces, for which adequate macrotexture evidently may be obtained in other ways.

Grooves may be longitudinal or transverse (cross-grooving). Only cross-grooving was discussed in the foreign documents in our collection.

Grooving may be molded with the concrete when it is poured (plastic grooving) or cut into an existing surface (tined grooving and diamond grooving).

Its geometrical parameters are depth d, width w, interval between grooves, s, and cross sectional shape (rectangular, trapezoidal, triangular. The interval s is frequently varied randomly to prevent tonal noise from resonances with the tire tread, in which case s should be specified by S_{min}, S_{max}, S_{avg} for completeness. (see diagram.)



For example, for a typical English random-spaced cross-grooving, d = 6 mm, w = 6 mm, s = 25-60 mm, cross section = rectangular (Ref. 61).

5.D.1 Cars

According to a Canadian study, plastic grooving is generally noisier than the cut grooves. Among the cut grooves, "diamond grooving" may be quieter than "tyne grooving" (Table 5-5).

Types of grooves	"Summer tire"	"Winter tire" (snow tire)	"Radial tire"
Diamond 1/8" deep (random grooved)	2.8	0.4	3.5
Diamond 3/16" deep (random grooved)	3.2	0.4	3.5
Tyne (not reported whether random)	10.4	3,1	7.9

Table 5-5

Noise Increases on Cut Groove Pavement Compared with Ungrooved Worn Concrete, for Passenger Car Tires

(97 km/h, or 60 mph. New tire measurement, measurements on the same car.) (36/Table 4)

These data in Table 5-5 show that the increased noise caused by grooving is greatest for cars equipped with relatively smooth-treaded tires and least for rough treads like snow tires. Evidently the snow tire is already creating a "rough" tire/road interface and the roughness from the grooving adds little additional noise.

Swiss data for a "summer tire" is comparable to that in the "summer tire" column of Table 5-5. When new, plastic-grooved concrete (4 mm wide x 3 mm deep x 25 mm interval) is compared to new concrete with ordinary texturing, the grooving added a flat 6-7 dB across the entire range of speeds studied (80-120 km/h) (3A/12).

5.D.2 Trucks

Fragmentary data shows an increase of up to approximately 6 dB when a worn existing concrete road is grooved, for a fully loaded tractor trailer at 72 km/h (45 mph).

Surface	Difference in noise level, dB, before and after grooving (trucks)
Worn concrete	Ref.
Diamond groove 3/16" (4.7 mm)	+ 5.5
Diamond groove 1/8" (3.8 mm)	+ 3.5
Texturized with "CMI-Rotomill" machine	+ 2.5

Table 5-6

Effect of Grooving on
Truck Tire Noise (Ref. 36)

5.E Wet vs. Dry Surfaces

5.E.1 Cars

Wet surfaces are noisier than dry ones for most tire/road conbinations (but not all of them), by up to 10 dB (9/Table 1). The amount of increase depends on the combination. Table 5-7 shows that with passenger "summer" (patterned rib) tires, water causes the largest noise increase on road surfaces with a smooth and fine structure.

Surface	Change in Noise Level, dB Speed (km/h) 50	 70
1. Ab16t (asphalt w. aggregate)	2.5	1.5
2. Agb16 (smooth)	6.0	3.0
3. Topeka (asphalt w. aggregate)	0.5	0.8
4. "Surface treatment" (rough stone surface dressing)	0	0.2

Table 5-7

Increase in Tire Noise from
Dry to Wet Conditions for Four
Road Surfaces and Two Speeds
("Summer Tires") (Ref. 35A/17).

Note that the increase is highest for the smoothest surface (#2) and lowest for the roughest surface (#4), also that the increases are very sensitive to speed.

A Swiss study got similar results right up through the "roughest" surface of all: cross grooved concrete.

Texture Depth	Surface	Change in Noise Level, dB Speed (km/h)		
		80	100	120
.34	Smooth worn concrete (seamless, 15 years old)	4	3	1
.38	Smooth Asphalt (Swiss AB10)	4	2	1
2.60	Surface treatment (dB 10/16)	3	2	3
.50	New Concrete (textured)	5	2	-
1.20	New concrete, grooved 4 mm w. x 3 mm d. x 25 mm	-1	-2	-

Table 5-8

Increase in Tire Noise from Dry to Wet Conditions for Five Road Surfaces and Three Speeds. ("Summer Tires) (Ref. 3A/12)

In fact, when the grooved concrete was wet, noise levels went down slightly, accouding to the data. Teh same effect was found for studded now tires, in a Norwegian study (35A/15-16). There it was hypothesized that the decrease might have been due to the dampening effect of the water on the rough tread type. Here it appears that the water may be dampening the effect of the rough surface, as "seen" by the tire. (35A/15-16). Another way of explaining it is that the water in the grooves effectively decreases their texture depth (3A/9).

Of course, one problem with obtaining repeatable results is controlling the degree of wetness. For example, the L_{10} for one case ranged as follows:

Dry road	77 dB
"Slightly wet" road	82-85
"Wet"	83-85
"Very Wet"	86

(No details given about type of road or tire)
(New Zealand, Ref. 8)

5.E.2 For Truck Tires

"If bulk water does lie on the surface, then the noise can be 7-11 dB higher than in the dry with truck tires.

However, if the road surface has enough drainage to drain away the surface water, such as the porous surface of friction course, then noise in the wet is hardly any higher than the noise in the dry." (10/187)

5.F Effect of Surface on Noise from Studded Tires

For four Norwegian surfaces (one smooth asphalt, two asphalts with aggregate, and one surface dressed with stones which protruded to make a rough surface, the differences in average tire noise ("summer" patterned rib, 70 km/h) were less than 3 dB. Thus when studded tires are used the road surface is less important for tire noise than when regular tires are used. Studded tires produce the most noise surfaces with a fine and even surface structure (smooth microtexture and smooth macrotexture (35A/15-16).

Wet vs dry.--The Norwegian study found that studded tire noise increased very little (0-2 dB) for wet surfaces (70 km/h), over a range of surface, and in one case found that the noise may have decreased slightly (although the change was small enough so that it also could have been a measurement error). The researchers hypothesize that if the decrease was real, it was because water could have a damping effect on studded tires with a rough tread type.

6. TIRE SCREENS

Vehicle borne screens provide a modest noise reduction benefit, according to several studies. Research into the possibility of reducing tire noise by various types of screens has been carried out in Sweden, West Germany, and the United Kingdom.

6.A Cowlings or Disks

As described briefly in Recherche Transport of July 1976 (39), British efforts were directed toward the application to the wheel and tire itself of a noise reducing screen or disk. The disk contained a laminated sheet of lead and provided an attenuation of 1.5 to 2 dB. The figure below from Recherche Transport depicts the British experimental cowling or disk.

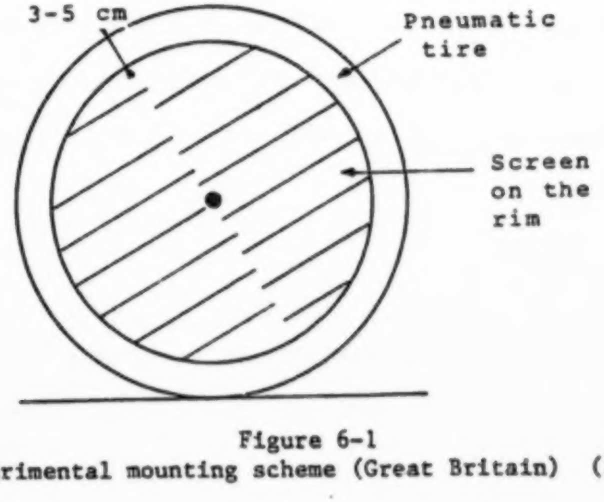


Figure 6-1
Experimental mounting scheme (Great Britain) (39)

The IFM Akustikbyran of Sweden has also looked at the use of cowlings or disks in order to reduce tire noise. Their research was reported in a study issued in 1976. (89) The following figure from their report shows the type of disk that they employed.

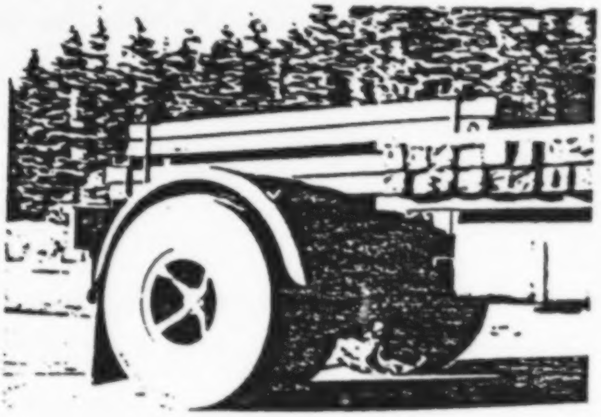


Figure 6-2. Scania-Vabis type L5383 with outer circular disks on the wheels (89)

The disk was made up of 3 mm steel sheets with rubber on the outer edges. Noise measurements were made when the truck was free rolling on dry and wet surfaces and in the speed range of 30-90 km/h. The attenuation observed was limited to 1-2 dB.

6.B Skirts

The IFM Akustikbyran also looked at a "skirt" that completely surrounded the vehicle. The picture on the following page from their report (89) presents their experimental screen.

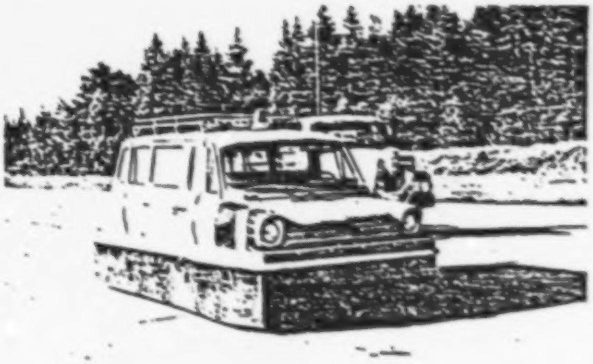


Figure 6-3. Ford Transit with rubber sheets along all sides. Radial tire with block-pattern of all-weather type. (89)

Their "skirt" was made of a rubber sheet and provided an air gap of 50 mm between the "skirt" and the road. The "skirt" provided a noise reduction of 7 dB at 50 km/h on dry roads but only 2 dB at 70 km/h. For wet roads the reductions were only 1-2 dB. They postulated that the limited effectiveness at high speeds might have been caused by the screen being too loosely designed.

6.C Enclosures

The most promising type of tire screen involves enclosures of individual wheels. The following figure from Recherche Transport (39) illustrates this technique.

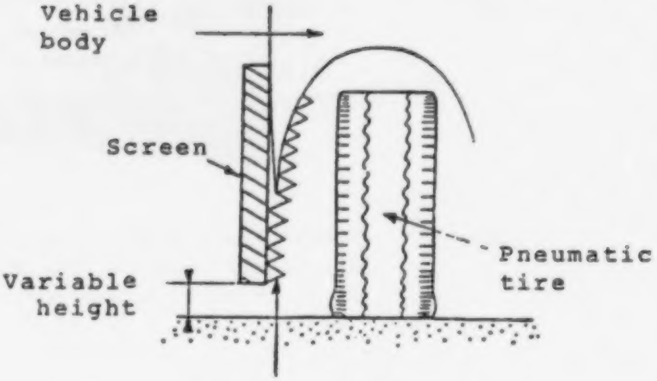


Figure 6-4

Experimental Mounting Scheme for a Screen (Sweden) (39)

In attempts to isolate tire noise from other sources the Technical University of Hannover in West Germany designed acoustical enclosures for tires. (17) The enclosures had a frame of perforated sheet metal which was covered by two different types of material. When 3 mm thick dense plastic was used as the enclosing material, a reduction in tire noise of 3-5 dB was found. When 3 mm plastic reinforced with lead powder was used an additional 1 dB reduction was obtained. Both of these materials were tested at 50 km/h and with a 50 mm road clearance. The technical University of Hannover states that up to a 10 dB reduction in noise would be possible if the enclosures could be lined with a highly efficient sound absorbing material.

The IFM Akustikbyran has conducted extensive research on the effectiveness of local enclosures in reducing tire noise. In a study reported in 1976 (89) they examined noise attenuation from tire screens made of steel sheets that used a flexible rubber curtain for the lowest 100 mm. The gap between the screen and road was varied between 5 and 100 mm. The picture below from their report presents the type of enclosure employed.

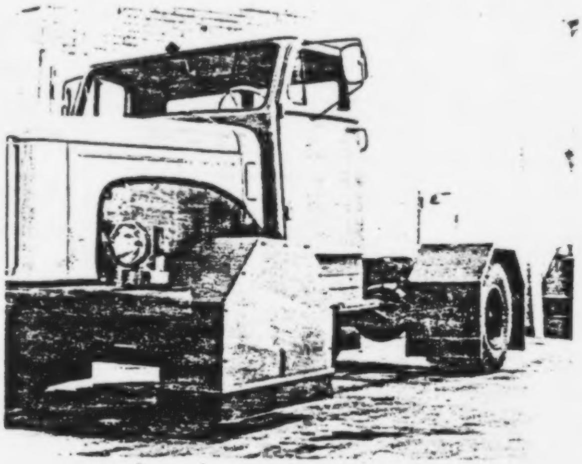


Figure 6-5

Scania Vabis L 5383 with enclosures. The back wheel enclosure is partially removed.
Front wheels: rib tires
Back wheels: winter-tire of cross-bar type (89)

They found that with enclosures on all wheels there was a noise reduction of 5 ± 2 dB on dry roads and on wet roads of $2 \pm {}^{4}_{2}$ dB. When noise absorbing material was used on the inside of the screens the resuction was 7 ± 3 dB for dry roads and 4 ± 2 dB for wet roads. Their data is presented in the table below from the IFM Akustikbyran report.

Road Condition	Velocity km/h	Scania Vabis L5383					
		Enclosure without absorber			Enclosure with absorber		
		20 mm dB	50 mm dB	100 mm dB	20 mm dB	50 mm dB	100 mm dB
Dry	30	-	3,2	-	-	3,8	-
	50	5,7	4,7	5,3	6,6	9,6	7,9
	70	5,5	5,1	5,2	8,3	8,2	8,7
	90	-	6,7	-	-	10,0	-
	Mean value	5,6	4,7	5,2	7,4	7,1	8,3
Wet	30	-	0,9	-	-	6,4	-
	50	2,5	6,4	4,8	7,8	5,0	6,0
	70	1,7	0,3	2,0	2,4	1,9	2,9
	90	-	2,1	-	-	2,5	-
	Mean value	2,1	1,9	3,2	4,3	3,6	4,2

Table 6-1

Insertion Loss in dB at 7.5 on a
Fine Graines Asphalt Surface
(89)

The enclosures did increase the operating temperature of of the tires as is shown in the figure below from their report.

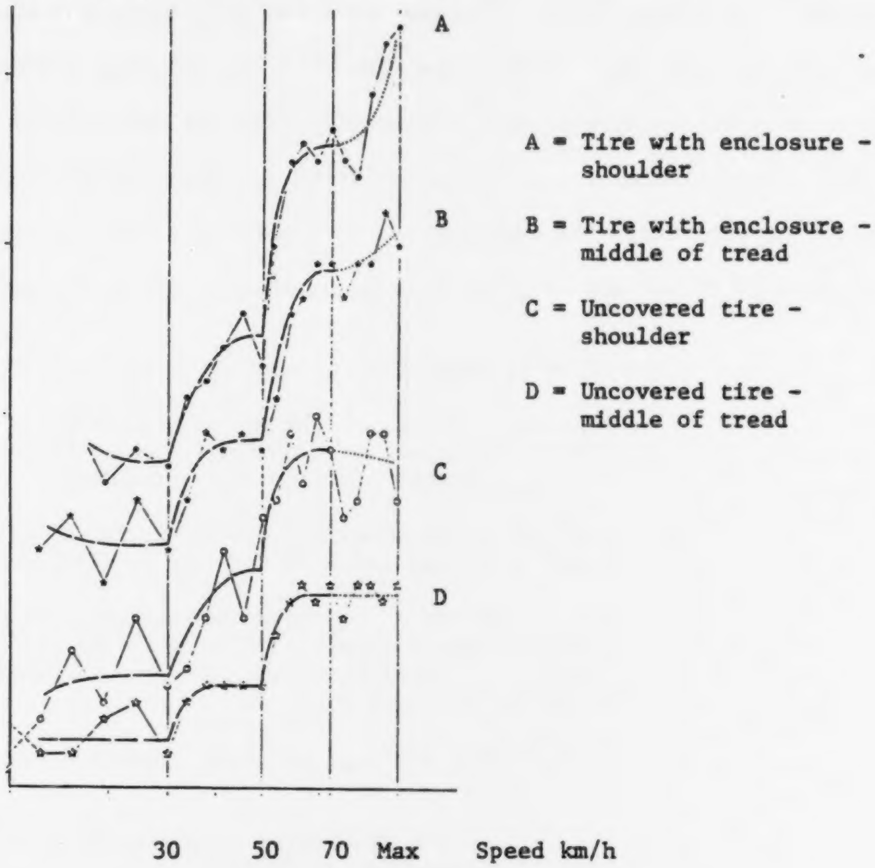


Figure 6-6

Tread Temperature of Enclosed Tires at Various Speeds and Driving Times (89)

However, IFM Akustikbyran states that the increase in temperature is not critical.

In two papers (31, 29) issued in 1978 the IFM Akustikbyran reported on follow-on studies to their earlier work on tire screens.

This research used the same vehicle and examined the effects of using larger clearances between the road and the screens and of using screens on the rear wheels only. In these tests the enclosures contained no sound absorbing material but were made of steel sheeting covered by vibration absorbing material. "Typical" tires for the vehicle were used - steel radial rib tires on the front and steel radial block/rib tires on the rear. The measurements were made on a "medium textured" surface (both wet and dry) and a rough surface at 50 and 70 km/h.

The following results were obtained during the study:

- Enclosures on all wheels and with clearances of 100, 150 or 200 mm all gave dB noise reductions on the "medium-textured" surface (dry condition).
- When the surface was wet the noise reduction was 1 dB for 200 mm and 3 dB for 100 mm clearance.
- For enclosures on the back wheels only, noise reduction was 2 dB with 200 mm and 3 dB for 100 mm clearance. When the surface was wet the noise reduction was only 1 dB.
- On the rough surface the noise reduction was less than 1.5 dB.
- For 50 km/h the enclosures were generally 0-1 dB less effective than at 70 km/h.
- The tire temperature rise caused by the enclosure was about 5° (typically from 46 to 51° C) for 2 hr continuous driving at 40-80 km/h with 24° ambient temperature.
- The attenuation for tonal components in the spectrum was better than the overall figures show. Consequently, the subjective noise reduction should be better than indicated by L_{eq} values.

The enclosures were found to have a substantial attenuation effect on dry roads in the frequency range of 200-500 Hz and above 4000 Hz. Between 500 and 4000 Hz the attenuation was insignificant. On wet roads, tire noise is increased in the 1000-4000 Hz range so the attenuation potential of the enclosures is reduced and their observed attenuation is insignificant.

The study concludes that enclosing all tires down to 200 mm or the rear tires only down to 100 mm gives comparable, acceptable attenuation. However, several problems were mentioned:

- The enclosures could hinder the movement of the vehicle by not providing sufficient clearance from the road or other objects. This is especially significant for vehicles in rough terrain or at construction sites. The study suggested some type of method that would raise and lower the enclosures.
- The temperature of the tire was observed to increase approximately 5° C. This could cause increased tire and brake wear. In order to overcome these problems the study suggested that a 5% decrease in temperature could be gained by a 10 km/h decrease in speed or a 20% decrease in load. In order to overcome the economic consequences of these actions the study suggested that the enclosures could be constructed in such a way as to admit cooling air.
- There is a possibility that the enclosures could become clogged with mud or snow. The study states that no evidence has appeared to show that these problems would develop in practice. In addition, the increased heat could contribute to melting the built up snow.

The study says that further operational tests are planned including long-term in-traffic tests. Only after these tests are completed can a total evaluation be made of the suitability of the enclosures for use in reducing car and truck tire noise. alternative types of enclosures will be evaluated on the basis of the type of vehicle, type of tires, use conditions, and economics.

7. STUDDED TIRES

A study (41) issued in 1974 by the Center for the Evaluation and Research on Noise of the Institute for Transportation Research in France states that the noise level from light vehicle studded tires is on the order of 80 dB. The measurements were made at 7.5 m and 80 km/h. This represents an increase of up to 16 dB above the 64 dB level they observed for longitudinally grooved (rib) tires.

In 1975 the Norwegian Road Research Laboratory reported a study (35) that dealt with the differences between the noise levels from studded and non-studded passenger car tires. They found that the noise level compared to ordinary (summer) tires increased approximately 3 dB on the average with the use of studded tires but up to 7 dB in some cases. In addition their measurements showed that the individual differences between tires were less when studs were used and that studded tires were noisiest on fine and even road surfaces.

Their study found that noise from studded tires increased in all frequency bands but that the largest increase was in the 250-2000 Hz range and especially on fine and smooth road surfaces. They felt that compared to non-lug (summer) tires, most of the noise increase was due to the addition of a snow tire tread, and that the further addition of studs played only a small part in the noise increase. Their results were based on measurements with one car only and with partially worn studded tires. Their report did say that newer tires and different cars may give different results.

The following are some of their measured results for exterior noise from their test vehicle. They felt that the same relationship present in this data also held for interior noise levels.

	Smooth Road		Rough Road	
	50 km/h	70 km/h	50 km/h	70 km/h
Ordinary tires	66.5 dB	73.5 dB	71.0 dB	74.0 dB
Snow tires	72.0 dB	76.5 dB	72.5 dB	76.5 dB
Studded tires	73.5 dB	75.5 dB	73.0 dB	77.5 dB

The Norwegian Road Research Laboratory plans a research program for 1978-79 (24) that will further clarify the contribution of studs to the total noise emitted from a vehicle and to evaluate different types of tires as alternatives to studded tires. They intend to address the question of whether the increased noise levels from studded tires are due to the studs or to the coarser tread pattern that this type of tire uses. Their research will consider studded tires, snow tires, ordinary tires, and "friction tires". "Friction tires" are a type of new generation tire that represents a Scandanavian production experiment for a winter tire using the increased friction of "soft" rubber rather than studs to provide better traction on ice and snow.

A study (34) issued in 1974 by the Akustick Laboratorium of Norway also looked at the noise from studded tires. In 1973 the Akustick Laboratorium measured the traffic levels in two locations, a through road and a four-lane highway. The passby traffic was counted per time at these locations and heavy vehicles were considered equivalent to ten light vehicles with regard to their effect on the noise level. Their measurements in March of 1973 reflected traffic in which approximately 70% used studded tires. They measured again in July 1973 to obtain control measurements of traffic without studded tires. Their data included the noise level, the average speed of the traffic, and the amount of traffic. From their measurements they concluded that studded tires probably do cause a somewhat higher L_{eq} on roads in densely populated areas when the average speed is below 50 km/h but that this increase in L_{eq} is not highly significant. However, at speeds of 80-90 km/h, studded tires cause a significant increase in L_{eq} of 3-6 dB.

The Technical Research Centre of Finland conducted a study (49) in 1975 that looked at the difference between noise levels from studded and non-studded tires. They found that the mean maximum noise levels measured on Finnish asphalt paved main roads at 7.5 meters were:

	Without Studs	With Studs
Light vehicles	79.8 dB	82.8 dB
Heavy vehicles	86.2 dB	87.3 dB

The values are based on 7366 measurements from traffic passby observations at 60, 80, and 100 km/h. Their results show that studs added 3 dB to the noise from car tires but only 1 dB to that of truck tires. The information provided did not state to what type of tires the studded tires were compared.

8. OTHER DESIGN OBJECTIVES

8.A Safety

As stated in a 1977 Dunlop Ltd. report (82), the wet roadholding performance of automobile tires has approximately doubled over the past two decades due to advances in tire construction and compounding technology. A similar but less dramatic improvement in performance has taken place for truck tires.

8.A.1 Traction

Recent work suggests that there may not be any hard and fast disagreement between road/tire combinations with good skid resistance and those with low noise. In fact, as Sandberg concludes, "there seems to be an optimum degree of macrotexture which at the same time gives acceptable skid resistance." (27/1) Sandberg cites six supporting references.

- LIEDL,W: "Der Einfluss der Fahrbahn auf das Gerausch profilloser Reifen und ein Beitrag zu seiner Erklarung." Automobil Industrie 3/77.
- SANDBERG, U: Vagbanekarakterisering med avseende pa dackbuller. Report No. 92, National Swedish Road Traffic Research Institute. (Our Ref. 16 and 16A)
- FULLER, W R, POTTS, R L: "A Study of Automobile and Light ruck Tire/Pavement Interaction Noise Levels." SAI-76-557-LA, Science Applications Inc, USA (under DoT Contract).

- KANEYASU, K: "Vehicle noise and tire noise." Annual Report of Roads, 1974, Japan Road Association, Tokyo, pp. 78-85.
- VERES, R E: "A Tire Noise Investigation and Test Method," SAE paper 760152, Soc of Automotive Eng, Warrendale, Pa, USA.
- WISLEDER, D E, JOHNS, J: "Traffic Noise Compared to Roadway Surfaces." NOISEXPO 75, National Noise and Vibration Control Conf., Atlanta, 1975.

Also supporting this conclusion are:

- An article by Walker and Major on work at the English Transport and Road Research Laboratories (10).
- A German article by Essers and Liedl (56, 56A), containing essentially the same information as the Liedl article (57).

If the texture depth is at least 1.0 mm, a high speed (100 km/h) wet BFC of at least .25 can be obtained from a wide variety of surfaces with a high degree of confidence. A BFC of .3 to .4 is associated with a texture depth of 1.5 mm. Little further improvement in the BFC occurs when the texture depth is greater than about 1.5 mm. (100/4-6)

Extensive tests using blank tires on various West German highways have shown that some of the roads with the best traction also have the lowest noise levels, and preliminary tests have shown that the same result holds for treaded tires. The surfaces were not described sufficiently to allow the crucial characteristics of these "good" surfaces to be identified, however.

The standard braking coefficient tester* for West Germany was used to test the traction of 15 different road surfaces, most of which were surfaces in use, but one of which was a low traction test surface. Two were new asphalt, whose traction was initially low until they were broken in through use. The standard test uses a "standard" tire, not described, dragged "frozen" behind a trailer at 80 km/h (50 mph) on a wet surface (1 mm water film, thin enough to prevent aquaplaning). The noise of a worn blank tire coasted over the same 15 dry surfaces at 60 km/h was measured using a close-in microphone mounted on the trailer. The braking coefficients were plotted against noise levels. The results showed that some of the surfaces with better traction were also the quieter surfaces (Figure 8-1).

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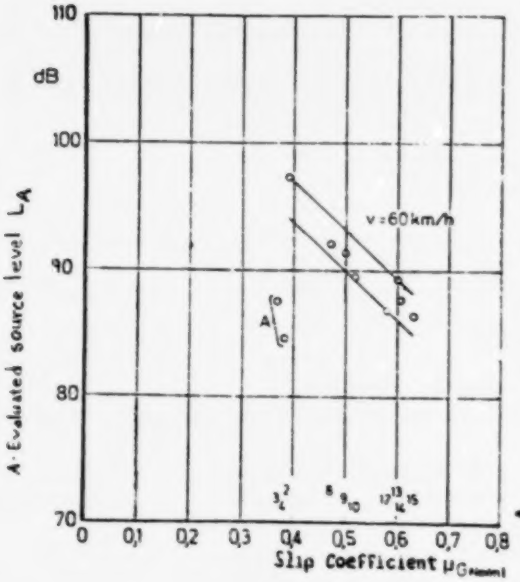
* Described in Section 5.A



1. Speed v = 60 km/h.

2. A: not yet sufficiently broken in asphalt roadways.

3. The numbers identify the surfaces in Table 8-1.

Figure 8-1

Relationship between noise level L_A of the blank tire freely rolling on different dry roadways and the slip coefficient $\mu_{G\ stand\ I}$ of the standard tire on the same roadways under wet conditions. (5 A/ii)

The best surfaces were all "asphalt concrete" from heavily travelled roads; the grain (probably the size of aggregate) varied from fine to rough, but the surface geometry of all was rated "very rough." These are surfaces 12-15 on the table below. On the other hand surfaces 8-10, noisier with less traction, were also asphalt concrete of "very rough" surface geometry (see Table 8-1). The only difference discernable from the descriptions is that the latter group were all surfaces from "country roads" rather than "heavily travelled sections."

The same relationships roughly held for the coast-by test repeated at speeds of 40 km/h and 100 km/h. These were also confirmed in tests with treaded tires (evidently, preliminary tests). It is planned to repeat the tests with production tires and with special test tires of simple geometry. (56)

Section	Identification of Surface	Useful Purpose
1	Bituminous sludges	Special test section
2	Worn concrete	Federal road
3	Relatively new asphalt concrete	Country road
4	New asphalt concrete with slight splitting	Federal road
5	Granite pavement	
6	Asphalt concrete with mean roughness	
7	Asphalt concrete with mean roughness	Country roads
8	Asphalt concrete with great roughness	
9	Asphalt concrete with great roughness	
10	Asphalt concrete with great roughness	
11	Red mastic of great roughness	Park surface
12	Asphalt concrete, fine-grained, very rough	
13	Asphalt concrete, coarse-grained, very rough	Heavily travelled
14	Asphalt concrete, coarse-grained, very rough	Test sections
15	Asphalt concrete, coarse-grained, very rough	

Table 8-1
Identification of Surfaces in Figure 8-1
Ref. 56A/9-10

Ullrich, also using blank tires, finds a great deal of scatter and concludes, for passenger cars, "a dependence of the rolling noise levels on the coefficient of slip is not to be found" (37A/11). (See Fig. 8-2)

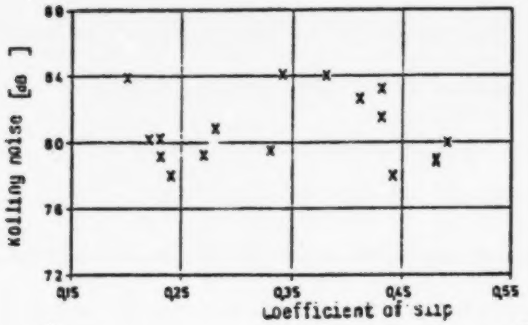


Figure 8-2

Rolling noise level of a test vehicle with non-profiled tires at 100 km/h as a function of the coefficient of slip of different concrete surfaces, measured with the Stuttgart tribometer (friction meter). (Ref. 37A/9)

Sandberg cites numerous U.S. and foreign studies showing that surfaces with a higher friction do not necessarily have a higher noise level (16A/4-5). It is unclear whether all of these studies dealt only with passenger car tires.

Nelson (98) has attemped to correlate tire noise with the relative difference in BFCs from 50 to 130 km/h, i.e.:

$$\frac{BFC_{130} - BFC_{50}}{BFC_{50}}$$

He shows that the larger the relative change in BFC, the louder the noise. The correlation is about the same for concrete and asphalt, but there is quite a bit of scatter in the data. Surfaces whose BFC's drop off sharply at the higher speeds are not desirable from a safety point of view. Nelson tells us they tend to be noisy as well (Fig. 8-3). Based on measurements of actual traffic (light = cars, etc., heavy = trucks over 1.53 mg), he finds a good correlation for light vehicles (Fig. 8-3), and a bad correlation for trucks (Fig. 8-4). Implicit in Nelson's method is that since the vehicles were travelling at steady speeds and there was an average mixture of tire types, other variables were somewhat controlled, and the only variable of statistical significance was the tire/road interaction.

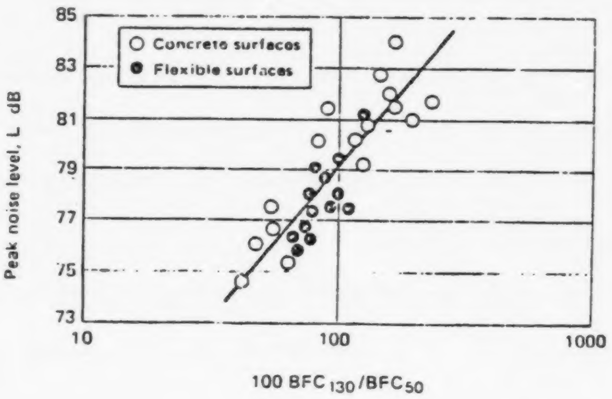


Figure 8-3

Light Vehicle Correlation Between Noise and Relative Change in BFC at High and Low Speeds

(Ref. 19)

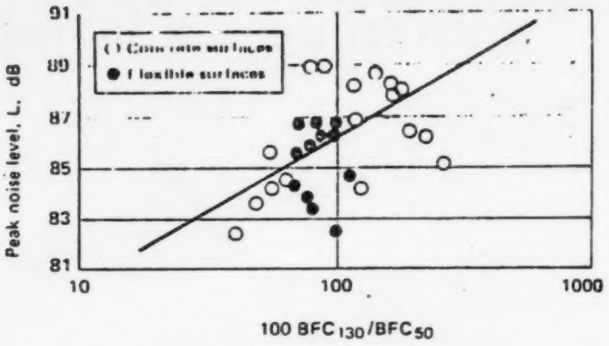


Figure 8-4

Heavy Vehicle Correlation
Between Noise and Relative Change
in BFC at high and low
speeds (19)

A related finding by Nelson is that two separate correlations exist for change in BFC and texture depth—one for concrete and one for bituminous surfaces (Figure 8-5). The texture depth was discussed in Chapter 5.

Walker (5/244 and 10/196) appears to agree with the others as far as cars are concerned. Especially good combinations of high traction and low noise are found with a proprietary surface called "Delugrip" (Figure 8-6), used with passenger rib tires.

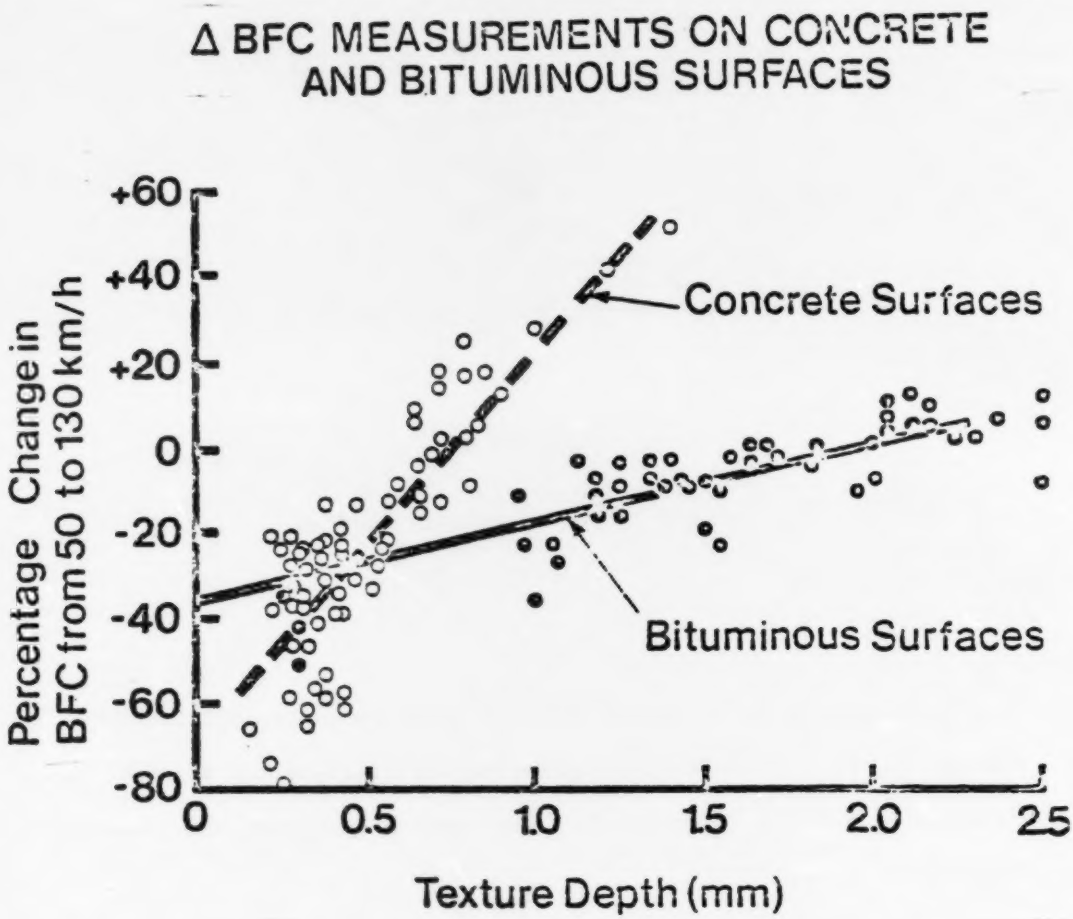


FIGURE 8-5

(Ref. 19)

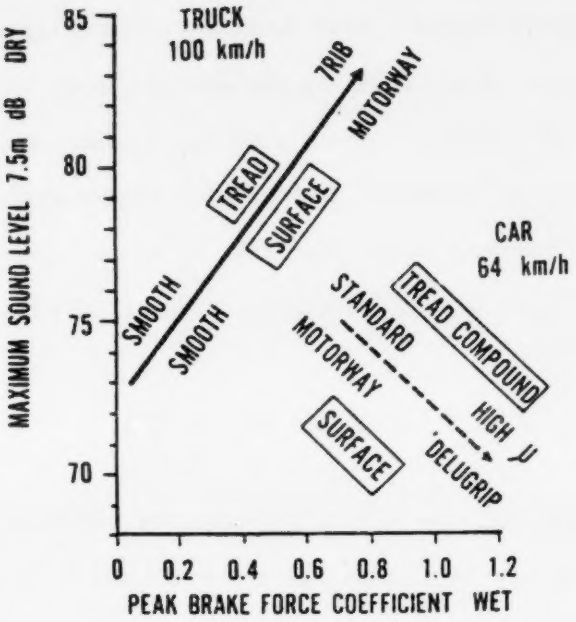


Figure 8-6

Vehicle Coasting Noise Related to Wet Grip

Delugrip is a very firm mixture of binder with various amounts of aggregate, presenting a surface of some porosity and characteristics of sharp microtexture that remain the same as the surface is worn down. (28)

Walker seems to suggest, however, that for trucks, higher noise levels are inevitable if one tries to achieve higher traction by a combination of more aggressive tread and rougher road.

In summary, Nelson's work looks very promising and should be examined in close detail when his definitive report is published later in 1979. The Delugrip surface also seems promising, particularly if it gives some noise advantage with heavy vehicles while improving their traction. However, it is clear that it is not possible to make more detailed judgements on the documents presently in the data base.

8.A.2 Radial Tires and Low Aspect Ratio Tires

Increased traction normally results in increased wear. However, the European trend to radial tires as mentioned in Section 4.B.5 and the trend to low aspect ratio tires as mentioned in Section 4.B.1 have increased tire mileage at the same time that wet roadholding performance has increased. The use of radial ply construction with its better wear characteristics allows the use of softer rubber compounds that provide increased traction. As mentioned in Section 4.B.5 the trend to radial tires is additionally important due to the fact that radial tires are quieter than bias-ply tires. However, as mentioned in Section 4.B.1 the trend to low aspect ratio tires tends to counteract this effect due to their increased noise emission levels.

8.A.3 Vehicle Speed

A related safety trend has been the lowering of speed limits from 70 mph to 55 mph. This has produced a significant increase in highway safety as well as a supplementary reduction in tire noise. As Figure 8-7 from an Ontario Ministry of Transport study (9) shows, the reduction in noise by reducing the speed limit from 70 mph to 55 mph ranges from 3 to 5 dB depending on the type of road surface used.

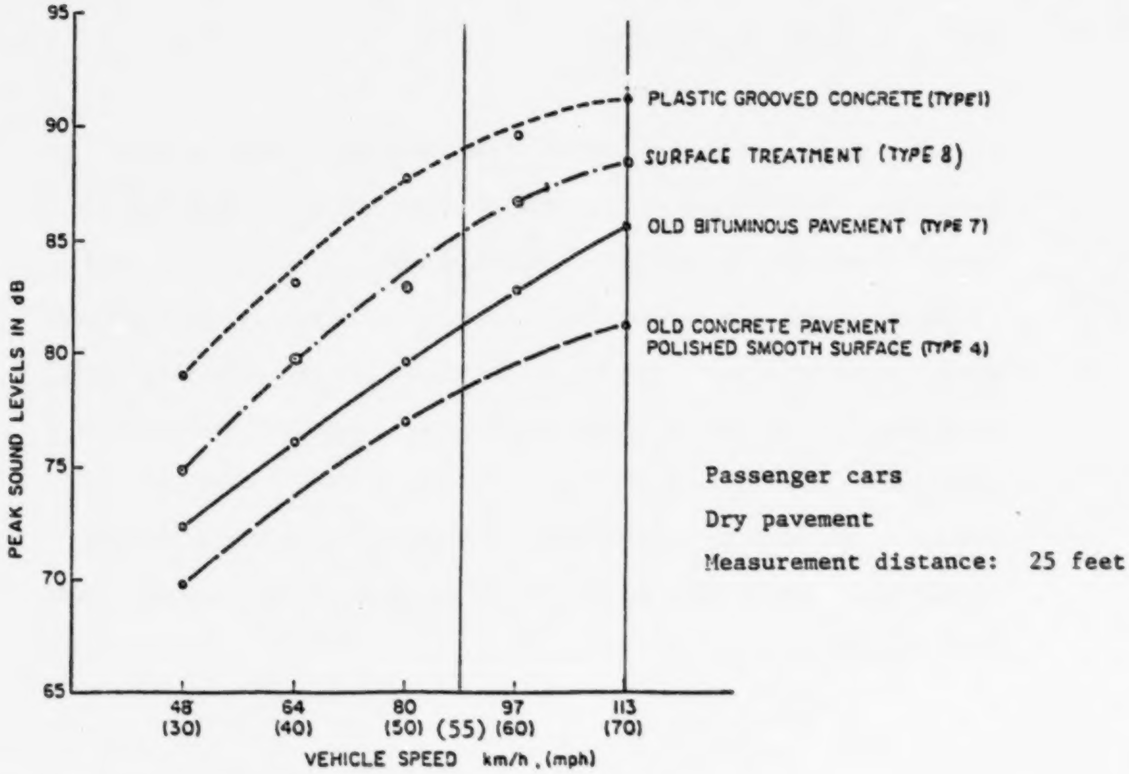


Figure 8-7

Noise Level vs. Vehicle Speed on
Various Types of Surfaces (9)

8.A.4 Temperature

Since safety is a combination of temperature and traction, tire and brake temperatures increased by tire enclosures used for noise abatement could develop into a safety problem. In this regard increased chances of tire and brake failure due to higher operating temperatures must be weighed against the noise benefits of the enclosures.

8.B Energy Conservation

The trend toward radial tires with their lower rolling resistance has produced greater fuel economy and subsequent conservation of energy. In addition, the reduction of speed limits from 70 mph to 55 mph was carried out primarily as an energy conservation measure. Both of these trends, as mentioned in the previous section, bode well for efforts to reduce tire noise emissions. The trend to low aspect ratio tires works counter to the current design goals of low noise and energy conservation. Low aspect ratio tires produce higher noise levels and higher rolling resistance and therefore lower fuel economy.

8.C Cost

It is known from direct observation that radial tires tend to be more expensive than bias ply tires. The trend to radials could, therefore, be a trend to increasing tire costs due to tire design. However, radial tires provide increased operating mileage and better fuel economy. These factors tend to reduce their overall cost.

It appears that optimizing noise performance will come as much from perfecting road surfaces as from other factors so it is important to consider the costs of road surface options for noise abatement. Since grooving or regrooving a road surface is quite expensive, provided accidents can be held to the same level, it is often less expensive to go with a quieter road. On the other hand, some of the newer, quieter surfaces may cost more than older surface types. Unfortunately no information is available on the costs of Delugrip, the surface that appears to have the best mix of advantageous qualities. However, this is partly beside the point because whatever surface is used depends upon the surface types that are available in a particular area. Therefore the extra cost of using the best type of surface from a noise and safety point of view must be calculated on a region by region basis.

9. CONCLUSIONS

9.A Generating Mechanisms

A 1978 study (37) by the West German Bundesanstalt fuer Strassenwesen states that measurements on laboratory wheels or drums with smooth surfaces tend to favor the air pumping mechanism while measurements on the road favor the vibration mechanism. However, with a rough surface on the drum or a smooth road surface this situation could be reversed, in our opinion.

Air pumping seems to be the most important mechanism when the road surface is flat and smooth and the tire has a pronounced tread. This situation provides much opportunity for trapping air in the cavities and pumping it out. The other major generating mechanism, vibration of the tire body, appears to be most important on roads with a greater surface texture. A rough road interacts with the rolling tire to produce impacts that cause the tire to vibrate and radiate noise. In situations where the tire body is set into vibration, these vibrations are also transmitted to the vehicle body and are radiated off as noise from the vehicle body parts. Aerodynamic noise and slip-stick noise appear to be generated mostly at higher speeds.

Rather than one generating mechanism being the sole explanation for tire noise it appears that all five postulated mechanisms apply, but to differing degrees in differing tire/road/operating condition combinations. In addition, the frequency spectra of noise from these mechanisms appears to differ. Tire body vibrations, vibrations transmitted to the vehicle body, and aerodynamic noise are in the lower frequency ranges. Noise due to air pumping falls in the medium range of frequencies and slip-stick noise generates at high frequencies.

9.B Measurement Methods

Laboratory wheels and drums and on-the-road pass-by tests are the measurement methods that appear to be used most often. Measurements utilizing a single wheel on a trailer are, however, gaining in use and importance. Pass-by tests are usually carried out at 7.5 m rather than at the 15 m distance used in the United States.

Near tire measurement, either on a vehicle or on a trailer, is the method that controls for the most variables. With a pass-by test, in order to test different road surfaces it is necessary to move from one surface to another. The measurement set up will never be exactly the same in any two tests. For near tire trailer or on the vehicle tests the whole vehicle and/or trailer is moved to the different surfaces and the measurement set up is kept intact and constant throughout. A trailer also allows testing of different size tires without changing the vehicle. The trailer provides the same vehicle effect for all size tires. Near tire measurements do suffer the problem of aerodynamic noise at the microphone. There are methods such as enclosures to attempt to overcome this problem.

The coasting pass-by test method is the one that provides the most realistic measurements of tire noise. It is conducted at a practical real life exposure distance and if the same vehicle is used throughout, allows for the control of many variables.

Laboratory wheel and drum measurement is the most cost effective methodology. It allows measurements to be made on many different tires year round in a controlled environment. This methodology appears, however, to be better suited for theoretical studies of tire noise than for practical noise abatement experiments.

The road/tire interface is the most important factor in tire noise measurement. In the use of laboratory wheels and drums it is often difficult to put realistic road surfaces on the drum surface. In addition, the curvature of the drum can cause further problems because a curved surface is not truly representative of the flat road that tires normally run upon.

9.C The Tire

In all parametric questions that were considered, light and heavy vehicle tires are different enough that they should be treated differently, although there is some overlap.

9.C.1 Trucks

Although it has been used for many years on automobile tires, pitch variation is just starting to be applied in the design of truck tires. Research has shown that changing the angle of the grooves in the tread can reduce tire noise without damaging other favorable characteristics of the tire. In addition, reducing the volume and length of tread grooves is a method to reduce tire noise. An example of this approach is the change from lug to rib-lug tires.

Smooth and straight-rib truck tires are believed to produce the lower limit in tire noise but may not be practical on a traction basis. The use of conventional rib patterned truck tires is therefore the next best approach to reducing tire noise from trucks.

The current trend is to the use of steel belted radial-ply tires. This tread has a favorable impact on truck noise because both lug and rib tires of radial design are quieter than lug and rib bias-ply tires.

The effect of wear on the noise from truck tires is not agreed upon. Most research results show an initial increase and later a decrease.

Research shows that noise from truck tires increases as internal tire pressure decreases. This is thought to be due to the increased contact area between the road and tire. In addition, a shift is seen to lower frequencies in the emitted noise as tire pressure decreases.

The operating temperature of the tire appears to have no significant effect on the emitted levels of noise. Speed of the vehicle, is however, a major factor to be considered. For truck tires a 9-12 dB increase is seen for each doubling of speed. In addition, "well treaded" tires show an increase in the frequency of the emitted noise as vehicle speed increases. Tires with longitudinal ribs show a constant frequency response across the normal range of operating speeds.

Increases in vehicle load cause an increase in the tire/road contact area. This is reflected in increased noise levels. The greatest increases come when load is increased from the unloaded to fully loaded state. This increase can be as much as 8 dB. Noise from rib tires appears to be affected little by load changes while noise from lug tires shows a much greater sensitivity to differing vehicle loading states.

9.C.2 Automobile

In order to abate the noise from automobile tires, designers have utilized variable pitches in the tread patterns for many years. This design procedure breaks up the dominant frequencies although it might not actually produce a lower noise level overall. It is now possible to optimize the tread sequence from a noise perspective by utilizing computer assistance in the tread designing procedure.

As with truck tires, smooth and straight-rib tires are the quietest types but they are not practical on a traction basis. The next most quiet type of tread design for automobile tires is the conventional rib patterned tire.

For automobile tires, as the aspect ratio decreases the noise increases. This means that high narrow tires are quieter than wide, fat tires. The trend is, however, in the opposite direction, toward low aspect ratio tires that are noisier.

Most studies have shown that radial tires are slightly quieter than bias ply tires of equivalent size and tread design. In the Dunlop study (10) the difference was reported to be less than 1 dB.

Operating temperature appears to have little effect on the levels of noise emitted by automobile tires. Studies do not agree on the effect of inflation pressure but agree that it is negligible. Only one study found it to be more than 1 dB. In addition, vehicle load in the normal operating range for automobiles seems to have no significant influence on tire noise.

Vehicle speed is one operating factor that has a major impact on the level of noise emitted by automobile tires. As with truck tires, a 9-12 dB increase in noise is seen with a doubling of vehicle speed. Also as with trucks, "well treaded" tires show a trend to higher frequencies in the emitted noise as vehicle speed increases. Longitudinally ribbed tires do not show this same trend to higher frequencies.

9.D The Road

Smooth surfaces are not the answer in solving tire noise problems both from a noise and safety point of view.

The road surface can be characterized by describing its macrotexture, its microtexture, and its skid resistance. The most common measure of macrotexture is the texture depth. Up to a point this descriptor correlates with noise for automobile tires. The correlation, if any, is unclear for truck tires. Within the range where texture depth correlates with noise for automobile tires the surface makes less and less of a difference as the tread becomes rougher or more "aggressive."

The Brake Friction Coefficient is the most commonly used measure of skid resistance. For automobiles there appears to be no necessary relationship between Brake Friction Coefficient and noise for all common types of tires such as rib, pattern-rib, and block designs. For non-grooved, dry road surfaces in actual use, the surface can make a difference of up to 6 dB in noise for car tires, 8 dB for truck tires.

Grooved surfaces alone can add up to 2-6 dB to the noise level emitted by tires. Some types of grooved surfaces are worse than others with plastic grooved surfaces being the worst and diamond grooved the best. The effect of grooves on the noise level becomes less if there is an aggressive tread on the tire, if the road is wet, or if studded tires are used.

Wet roads almost always are much noisier than the same surface when dry. The biggest difference between wet and dry noise levels occurs with either very smooth road surfaces or smooth tread patterns.

One new, moderately textured road surface material, Delugrip, tested in England seems to optimize both skid resistance and noise. This material has been developed by Dunlop Ltd.

The Delugrip surfacing material seems to be the best surface available from a low noise and high skid resistance point of view. The second best surfaces are textured concrete or porous asphalt. Surface dressings seem to have variable effects, but generally seem to cause higher noise levels than other surfaces with comparable texture depths and/or skid-resistance characteristics. The worst types, from a noise perspective, have rocks sticking up above the binder material.

9.E Tire Screens

On-the-wheel cowlings and disks, and "skirts" that enclose the whole bottom of the vehicle appear to provide insigificant amounts of attenuation. Screens that enclose the wheels alone show promise especially in dry road situations. However, more research appears to be needed in order to ascertain the severity of potential problems that exist with local tire enclosures:

- Enclosures could hinder vehicle movement and road clearance
- Tire and brake temperature show an increase when enclosures are used
- Enclosures could become clogged with mud and snow
- Enclosures could have a low acceptance value with consumers due to their visual appearance.

9.F Studded Tires

There seems to be agreement that studded tires increase tire noise levels, at least for automobile tires. There is no real agreement, however, on the amount of this noise increase. Research results range from a 3 dB increase to a 16 dB increase depending upon the source.

One theory is that the effect of the associated, more aggressive tread is more important than the effect of the studs themselves. Studded tires are also important because in addition to causing higher noise levels themselves, they tend to tear up the road surfaces and make them noisier for other types of tires to run upon.

9.G Some Recommendations for Further and Improved Tire Noise Research

In order to improve tire noise research, better reporting of that research is called for. Studies should include better specifications of the tires used including pictures of the tread patterns tested and listings of the brand names utilized. Better specification is required of the road surfaces tested upon, including descriptions of the texture depth and the Brake Friction Coefficients. A cross sectional diagram of a typical surface segment at least one-third meter long would be very desirable. Inclusion of a picture of the road/tire contact patch in a tire noise research report would be helpful. This would show the effective length of the tread and the effective length of the resonant cavities between the road and the tire.

In the design of research projects, it would be very advantageous if all tire noise tests (laboratory drum, pass-by, etc.), included several internationally standard tires. These tires should have one or two of the most typical tread patterns.

In addition, it appears that further research is called for in order to examine the potential use of "Delugrip" road surface material. In view of its promising characteristics (pp. 8-7 to 8-10), it is necessary to see what obstacles, if any, exist to its widespread use.

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